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14-channel neurofeedback with Auto Train Brain improves the left lateralization of the brain in dyslexia: A pilot study

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Abstract

Auto Train Brain is a neurofeedback-based mobile application that increases reading comprehension and reading speed in dyslexia with EMOTIV EPOC-X which has 14 channels. The clinical trials have been completed on dyslexia beforehand. The left hemisphere-related deficits are known in dyslexia. In this research, we have investigated the positive long-term effects of Auto Train Brain to improve the variance of gamma band sample entropy across neurofeedback sessions. The previous research indicates that the increase in the variance of the gamma band entropy shows the increased adaptations in the functional networks. 14-channel neurofeedback with Auto Train Brain increases the variance of gamma band entropy in the left temporal lobe (T7) over the right temporal lobe (T8) which may be translated as the adaptations of the functional networks in the left temporal region are increased after 100 sessions of neurofeedback in terms of electrophysiology.

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I. Introduction

Dyslexia is a subcategory of Specific learning disorders according to DSM V criteria[1]. Some people struggle with reading, despite having IQs that are normal or above average[2]. Regarding the underlying cause of dyslexia, numerous theories have been proposed. The genetic origin of dyslexia is the most well-known of these explanations[3]. Children who

have dyslexia are more likely to have dyslexic parents[4]. The other common theories about dyslexia are that genetic predisposition, environmental conditions, maternal stress, maternal activated-autoimmune response during pregnancy, and infections during pregnancy are the root causes of this phenomenon to happen[5]. Newer theories suggest that this condition is the result of a delay in brain development. According to the "Delayed Neural Commitment (DNC)" theory, dyslexic children take longer to develop (and rebuild) the neural networks that support learning to read, in addition to having delayed acquisition of skills[6]. The framework offers a crucial time link between the early development of language, and speech networks, and the development of executive function networks[6]. Dyslexia is characterized by marked hypoactivation within the reading network, disrupted functional connectivity, and differences in structural connectivity in certain fiber tracts[7].

Even if children with dyslexia receive the necessary support education and adequate nutrition, it takes a very long time to close the gap between their peers[8]. Sometimes this difference cannot be closed during their lifetime. One or more parts of phonological processing are missing, such as the ability to consciously manipulate speech sounds (phonological awareness), to temporarily store phonological information in the verbal short-term memory, and to quickly retrieve long-term phonological representations[9].

Another theory about dyslexia is related to maternal activated-autoimmune response during pregnancy. Neurodevelopmental pathways are altered before birth. The immune response in the child is altered postnatally[10]. Excessive neurotransmitter formation triggers an autoimmune response, and inflammation begins due to the insufficiency of fatty acids[11]. The presence of inflammation delays the development of the brain[12]. As long as the inflammation continues after birth, brain maturation lags continue[13]. The development of the left brain and left lateralization of the brain is not yet completed in dyslexia[14]. Establishment of the left-brain dominance is important before the child reaches school age[15]. Visual and auditory cues must be processed quickly in the left posterior lobe in order for the child reaches the maturity required for the development of reading skills.

Another body of research asserted that individuals with dyslexia may exhibit a disordered interhemispheric functional asymmetry[15]. As a result, the corpus callosum of the dyslexic brain undergoes alterations that impair the flow of motor and sensory information between the two hemispheres.

It is hypothesized that there is a disconnection syndrome in the left temporal lobe of dyslexia[16]. QEEG measurements display the increased slow brain waves in the left temporal region of the dyslexic brain[17] and/or there may be general EEG slowing. Temporal lobes are important for brain maturation and functional connectivity, and this connectivity seems missing in dyslexia[18].

There are various subtypes of dyslexia. A number of recent studies have also discovered that dyslexia has been strongly linked to various characteristics, including underlying basic auditory processing deficiency[19], impaired visual processing[20], attentional deficits[21], defective eye movements[22], and irregularities of processing[23][24] and some have defects in combining the visual and auditory input in the left angular gyrus[25]. People with dyslexia are unable to efficiently decode written letters (graphemes) into their corresponding sounds (phonemes)[26]. Apart from the cortex, some subcortical structures may also be affected[27]. According to the cerebral deficit theory[28], deficiencies are brought on by a lack of development of articulatory skills, which in turn comes from an ontogenetic cerebellar malfunction. The cerebral deficiency theory may provide behavioral explanations for the difficulty of people with dyslexia in time estimating,

motor skills, working memory, and balancing tasks.

Dyslexia causes problems in understanding words, pronunciation, and syllables. Because of this, a child with dyslexia frequently struggles with language and verbal expression and is unable to distinguish between words based on their phonemes due to poor hearing and comprehension skills. These children are normal in other aspects or just a little smarter than average. They might be daydreamers dealing with low self-esteem, anxiety, and despair as a result of their academic struggles[29].

It is known that gluten-free diets[30], special education, neurofeedback[31][32], and multi-sensory learning[31] are the only effective solutions to reduce the symptoms of dyslexia. It should be noted that these solutions do not cure the root cause of dyslexia, they only improve brain maturation.

According to numerous studies, children with dyslexia have slow waves at FC5 and F7 and do not desynchronize beta-1 activity while performing a reading task in regions connected to Broca's area (FC5; speech production, articulation) and the Angular gyrus (CP5, P3), understanding semantics and mathematics[33] as well as the left parieto-occipital area (P7, O1)[34]. Right temporal and parietal (P8 and T8) areas of the brain have elevated sluggish activity in children with dyslexia[35]. According to the researchers, there is a disruption in the left temporal region[36]. Additionally, there may be a high level of frontal sluggish activity in individuals with dyslexia and ADHD. The coherence increases symmetrically. At T3 and T4, the delta and theta bands exhibit a symmetric increase in coherence, while the alpha and beta bands exhibit a distinct right-temporal central increase in coherence[35]. Bi-hemispheric hyper-coherence (between T3 and T4) appears in the delta and theta bands, however, between P7 and O1, there is hypo-coherence in the delta, theta, and alpha bands. Dyslexia is accompanied by issues with the gamma band and less functional connections[37][38]. The left and right temporal lobes are the sources of healthy functional connections. During healthy brain growth, the temporal lobes begin making new connections to other lobes, namely the frontal lobes, the parietal lobes, and the occipital lobes. Large-scale longitudinal healthy pediatric neuroimaging study results showed nonlinear changes in cortical gray matter, with a preadolescent increase followed by a post-adolescent reduction for healthy individuals, while they validated linear increases in white matter. The developmental curves for the frontal and parietal lobes peaked at around age 12, and for the temporal lobe at around age 16, but cortical gray matter increased in the occipital lobe through age 20[39]. These regional variations in cortical gray matter were present. As a child gets older, the connections between the right and left hemispheres become more stable, and the left hemisphere begins to develop more rapidly as a result of an increase in mental tasks. After becoming an adult, the brain balances its workload between the two hemispheres, allowing both to develop. It is well recognized that dyslexia suffers from poor neuronal connections, issues with functional connectivity, and a lack of grey matter production that also impairs working memory. As a result, treatments for dyslexia that lessen the disconnection syndrome, boost coherence, and raise entropy are pertinent and appropriate.

A significant connection between reading problems and auditory processing issues can be seen in the left temporal low activity region. Similar results offer neurobiological proof of underlying nervous system dysfunction in the temporo-occipital and parietal-temporal areas of the brain, among other posterior brain regions. Dyslexia may be significantly impacted by these unusual abnormalities in the left temporo-occipital region of the brain.

It is well established that neurofeedback can lessen dyslexia's consequences. The EEG data are read and displayed to the subject in real-time. The subject acquires more control over their brain through operant conditioning[40]. It has been

demonstrated that this phenomenon may change, and add weak connections that help the subject pay attention and learn better when the user learns to manage a particular area of the brain[41]. According to APA guidelines[42], neurofeedback is a "possibly efficacious" technique. It is difficult to demonstrate neurofeedback's effectiveness. Typically, clinical studies have been conducted to demonstrate advancements in the psychometric tests used before and after the investigation. According to several studies, neurofeedback leads to improvements in brain structure[43]. Participants showed improved functional connectivity of the sensorimotor resting state network and increased fractional anisotropy (FA) in the corpus callosum after one hour of NFB training. The default mode network also showed increased functional connectivity[44]. fMRI is typically used in this study to display the strongly linked brain regions following neurofeedback. It is challenging to demonstrate changes in the brain following neurofeedback using QEEG. There is research that shows the causality between neurofeedback and cognitive improvement[45][46][47][48].

Auto Train Brain is an advanced solution that includes neurofeedback from 14-channels, multimodal learning, and special education principles[31]. Machine learning algorithms are built-in features of Auto Train Brain.

Previous research investigated the long-term effects of 14-channel neurofeedback with Auto Train Brain[49]. It was discovered that the variance of the gamma band entropy was increased, showing the brain’s flexibility is enhanced. Using gamma band entropy variance is a good measure to understand the increased functional connectivity in certain regions across neurofeedback sessions.

In this research, we have compared the efficacy of 14-channel neurofeedback and that of 5-channel neurofeedback for dyslexia with Auto Train Brain in terms of variance in gamma band entropy changes after neurofeedback sessions.

II. Materials & Methods

A. Subjects & Experimental data

In this experiment, 40 dyslexic children participated providing their written consent both from themselves and from families according to the rules set by the research ethics committee. Their ages differ from 7 to 10 (34 males, 6 females). They have used Auto Train Brain (a clinically-tested mobile app for applying neurofeedback from 14 channels or 5-channels) more than 100 times to improve their reading speed and reading comprehension. The recruitment period was 6 months.

The children in the experimental group were diagnosed with dyslexia by psychiatric professionals, who then recommended that their families use Auto Train Brain at home. The TILLS tests were used by psychologists and psychiatrists to examine whether the individuals met the DSM-V dyslexia criteria. The children chosen to participate in the experiment were chosen at random. The participant's primary goal in the retrospective study is to use Auto Train Brain software as a neurofeedback device at home.

The participants utilized Auto Train Brain before leaving for school in the morning. The study's inclusion requirements stipulated that participants must be of middle socioeconomic status, be drug-free, and have dyslexia as their only comorbid condition, and be aged between 7-10. They lived all around Turkey in various cities. A survey of the parents of

the children was done to assess their socioeconomic position. The survey asks questions about employment, education (elementary, secondary, and postsecondary), and income (low income 6,000 TL, middle income 6,000 TL to 20,000 TL, high income >20,000 TL) (staff, blue-collar workers, white-collar workers).

We made an a priori power calculation to predict the sample size using G*power. We set the effect size as 0.63, which was calculated from the pre-and post-TILLS descriptive scores of the experimental group who did not have comorbidities in the original clinical trial of Auto Train Brain, set the alpha value as 0.05, set power (1-beta) as 0.95, set the T-Test and RCT as input parameters. The sample size for the experimental group was calculated as 67, and the sample size for the control group was calculated as 67. So, our study is a pilot study. In the future, we will repeat the experiment with more people.

B. QEEG recording

In the experiments, EMOTIV INSIGHT2 and EPOC-X headsets are used. The EEG data was read with 2048 per secs per channel -128 per secs per channel down sampled. EEG data were converted to the frequency band data with EMOTIV's standard procedures. The frequency band data is binned as follows: Theta (4-8 Hz), Alpha (8-12 Hz), Beta-1 (12-16 Hz), Beta-2(16-25 Hz), and Gamma (25-45 Hz). The artifacts were removed with a high pass filter (>100 Hz). EMOTIV APP is used for the calibration of the headsets, each electrode is soaked well and ensured that EEG data is read with top quality. The recorded channels were AF3, T7, P7, T8, and AF4 for EMOTIV INSIGHT2 and the recorded channels were AF3, F3, F7, FC5, T7, P7, O1, O2, P8, T8, FC6, F8, F4, and AF4 for EMOTIV EPOC-X.

The EMOTIV EPOC-X, a commercial wearable EEG device, was used for the recordings. One of the most popular sensory EEG devices for lifestyle applications is the EMOTIV EPOC-X, which consists of 14 sensors and associated felt pads inserted in the scalp in accordance with the International 10-20 System (AF3, F3, F7, FC5, T7, P7, O1, AF4, F4, F8, FC6, T8, P8, and O2). As reference channels, two more rubber electrodes were inserted into the mastoids. The connection between the electrodes and the scalp is made using the saline liquid solution that has been administered to all of the felt pads of each sensor, and the sampling frequency is 128 Hz.

C. Neurofeedback treatment protocol and multi-sensory learning method

Auto Train Brain is a mobile application that uses neurofeedback and multi-sensory learning principles. It is used with the EMOTIV EPOC+ headset. It is a non-invasive solution, that offers continuous brain performance improvement for both adults and children without any side effects. It reads QEEG from 14 channels, processes these signals, and provides real-time visual and auditory, online neurofeedback. Auto Train Brain is a patented software (patent number: PCT/TR2017/050572) specifically designed for people with dyslexia. Within this software application, a system and method for improving reading ability and cognitive functions is proposed. The system relies on a distinctive protocol of multi-sensory learning and EEG neurofeedback. The EEG neurofeedback protocol is explained below:

- Reduce theta waves at the Broca area in the brain if above the threshold;
- Reduce theta waves at the Wernicke area in the brain if above the threshold;

- Find the channels with the maximum absolute power of theta waves at the left hemisphere and reduce absolute theta for those channels; and
- Find the channels with the maximum absolute power of theta waves at the right hemisphere and reduce the absolute theta for those channels.

A positive reward is a green arrow on the screen, negative feedback is a red arrow and a "beep" sound. With a positive reward, the score displayed on the screen is increased. If the slow brain waves of the subject are above the norm threshold, a red arrow is presented on the screen and the subject is asked to try to turn it into a green arrow. After the neurofeedback session, a phoneme-grapheme matching alphabet teaching system is presented. One of the significant differences between the currently available neurofeedback systems and Auto Train Brain is that it combines neurofeedback with multi-sensory learning principles.

D. Study design

All subjects used Auto Train Brain (a mobile phone application) more than 100 times, for randomly chosen 20 participants, their brain waves are read using EMOTIV INSIGHT for 5 channels, for the rest 20 participants, their brain waves are read using EMOTIV EPOC-X for 14-channels and visual and auditory neurofeedback is given for 30 minutes. After the neurofeedback session, multi-sensory alphabet learning is studied for 15 minutes.
With some assistance from their families at home, the participants completed the 30-minute neurofeedback sessions. Each participant utilized it while seated at a table at home throughout the neurofeedback session. As their parents are told to do in advance, there were 40 centimeters between the subject and the smartphone app. The participants used Auto Train Brain's arrow neurofeedback interface.

At the end of each session, session average data for each frequency band was saved to the database. During the neurofeedback session, sample entropy was calculated for each frequency band data[13]. Sample entropy is the minus of the logarithmic probability which measures the similarity of two sequences. If the two sequences of m consecutive data points, that are similar to each other (within given tolerance r), will remain similar at the next point (m + 1) in the dataset (N), then the sample entropy would be higher. N is the number of samples in the session data. Normally, sample entropy is calculated based on EEG data series, however, in our calculations, we have used QEEG data as we have not reached raw data from EMOTIV INSIGHT2 or EPOC-X.

The feature set consists of 5 variables mapped from 5 channels for EMOTIV INSIGHT, and 14 variables mapped from 14 channels for EMOTIV EPOC-X. The measures are gamma band sample entropy values calculated from QEEG band power values.

E. Statistical Analysis

The statistical analysis was performed with SPSS 22. The regression analysis has been performed and R square values are reported. The increase in the variance of gamma band entropy (y-axis) in the left posterior region in the 100

sessions (x-axis, 1 bin= 10 sessions) was tested for the significance of the regression slope coefficient. It was checked whether our model is a significant predictor of the outcome variable using the results of ANOVA for regression (The change in the variance of gamma band entropy (y-axis) in the left (T7) and right temporal(T8) regions versus session groups (x-axis)).

III. Results

A regression line is drawn (the x coordinate is the session numbers and the y coordinate is the variance of gamma band sample entropy for each bin). The findings suggest that long-term neurofeedback use increased the variance of gamma band sample entropy, but we are unable to identify any long-term improvements in the gamma band sample entropies across sessions.

The 100 consecutive sessions have been merged into 10 bins. Next, we determined the variance of each bin's gamma band sample entropy. Ten bins were present. We have shown the gamma band sample entropy values' bin number vs variance. In both headsets' left posterior regions, the gamma band sample entropy variance rose over time (T7).

For a 14-channel EEG headset, the regression line yields R^2=0.78 when the first 30 sessions are excluded [$F_{(1, 7)}$ = 15.38, p=.01] (Figure 1). R^2 for the regression line is 0.50 when the first 30 sessions are also included [$F_{(1, 10)}$ = 8.97, p=.01] (Figure 2). In both instances, the linear regression lines' slopes were upward statistically significantly.

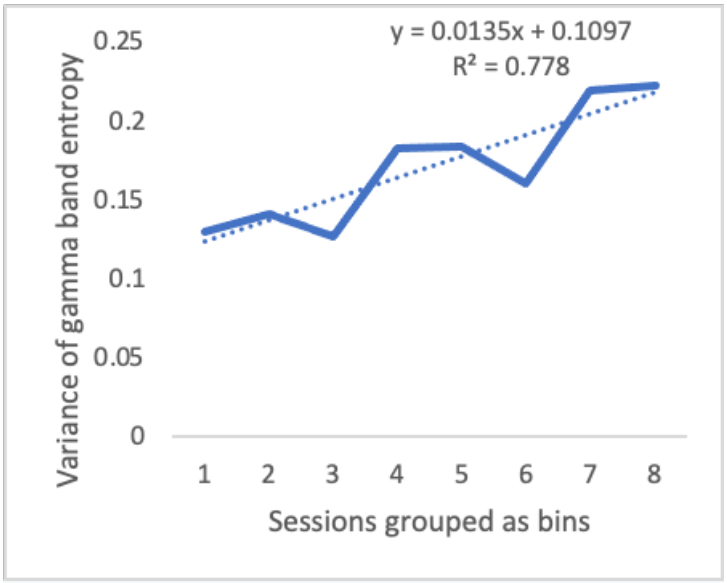

Figure 1. *The increase in the variance of gamma band entropy (y-axis) y in the left posterior region after 30 sessions (x-axis, 1 bin=10 sessions) for a 14-channel EEG headset*

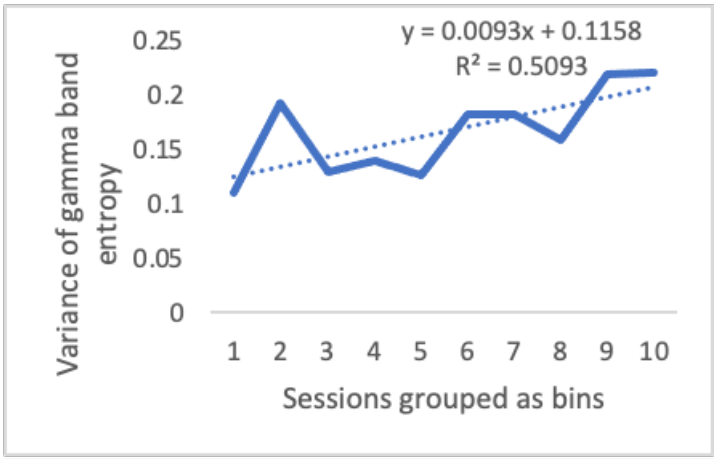

Figure 2. *The increase in the variance of gamma band entropy (y-axis) in the left posterior region for a 14-channel EEG headset in the 100 sessions (x-axis, 1 bin= 10 sessions)*

In the first 40 sessions, the regression line for a 5-channel EEG headset yields R^2=0.69 [$F_{(1, 4)}$ = 4.66, p=.16] (Figure 3). R^2 for the regression line is 0.48 for the following 60 sessions [$F_{(1, 6)}$ = 5.8, p=.07] (Figure 4). In both instances, the linear regression lines' slopes were upward but not statistically significant.

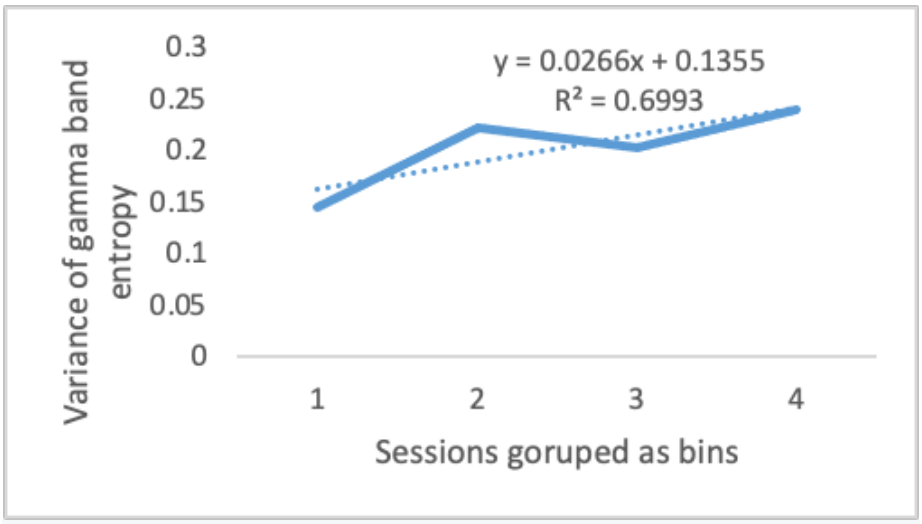

Figure 3. *The increase in the variance of gamma band entropy (y-axis) in the left posterior region for a 5-channel EEG headset in the first 40 sessions (x-axis, 1 bin= 10 sessions)*

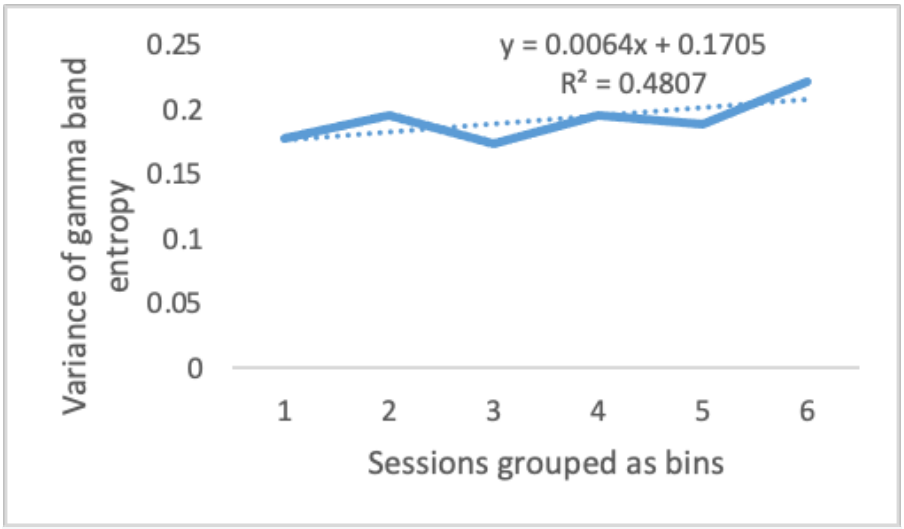

Figure 4. *The increase in the variance of gamma band entropy (y-axis) in the left posterior region for a 5-channel EEG headset in the next 60 sessions (x-axis, 1 bin=10 sessions)*

For a 14-channel headset, the variance of the gamma band entropy changes in the left temporal and the right temporal regions in the 100 sessions are plotted as follows:

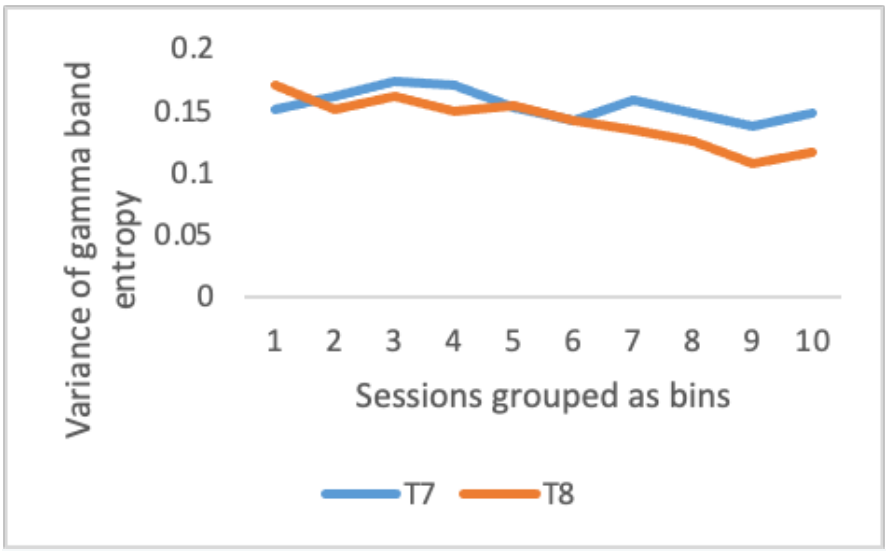

Figure 5. *The change in the variance of gamma band entropy (y-axis) in the left (T7) and right temporal(T8) regions for a 14-channel EEG headset in the next 100 sessions (x-axis, 1 bin=10 sessions)*

Figure 5 shows that at around 20th sessions, the left lateralization of the brain takes place and the variance of gamma band entropy becomes permanently dominant for the left temporal region after 60 sessions [$F_{(1, 6)} = 20.79$, p=.0038].

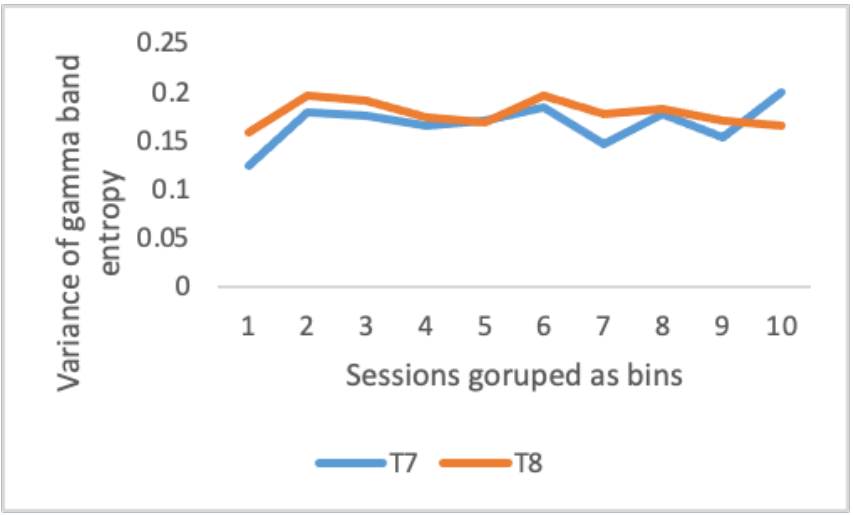

Figure 6. *The change in the variance of gamma band entropy (y-axis) in the left (T7) and right temporal(T8) regions for a 5-channel EEG headset in the next 100 sessions (x-axis, 1 bin=10 sessions)*

Figure 6 displays the gamma band variations over sessions for 5-channel neurofeedback with Auto Train Brain in the left and right temporal lobes. Left hemispheric dominance begins to occur only after the 100th session, which is twice as long as with 14-channel neurofeedback [$F_{(1, 10)} = 1.20$, p=.20].

IV. Discussion

In prior clinical research, Auto Train Brain was shown to be useful for children with dyslexia[31] with pre- and post-TILLS test comparisons. Their reading comprehension and reading speed were increased after 60 sessions and their entropy was increased. With 14-channel and 5-channel EEG headsets, we looked into the long-term use and the beneficial impacts of Auto Train Brain in this study in terms of electrophysiology.

In the first 20 sessions of use, 14-channel neurofeedback in the left posterior region causes a sharp increase in the variance of the sample entropy in the gamma band. With 5-channel neurofeedback, this rise requires twice as many sessions; after 40 sessions, the variation of the gamma band entropy peaks, and the brain begins to adapt.
As children adjust to and learn neurofeedback, we predict that numerous metabolic changes occur in their bodies as well as their brains and that the learning effort is particularly intense during the first month.

Given that dyslexic people are eager to employ their right hemisphere for mental tasks, the variation of the gamma band entropy increases first in the right temporal regions for dyslexia. After crossing a certain point, the burden becomes too great for the right brain, causing the left temporal region to begin to form new connections as we observe the left hemisphere's gamma band entropy variance increasing.

The hemisphere that is utilized frequently is initially more activated as we increase our mental burden, but as we do, the temporal region of the other hemisphere begins to become more active. Between the nearby temporal regions, new functional networking occurs. Therefore, it is possible to imagine that the increase in gamma band entropy variance shows

that functional connectivity is under construction to be enhanced. The variance of the gamma band entropy in the region begins to decline after the functional networking is enhanced and optimized fully, allowing the other regions to be built and developed more (Figure 5).

The variation of the sample entropy in the gamma band is reduced after the 20 sessions for 14-channel neurofeedback and after the 40 sessions for 5-channel neurofeedback with Auto Train Brain, and we assume that the functional networks prune and stabilize after some building and optimization. In the following sessions, there is an increase in the variance of the gamma band entropy. There are two further steps of pruning for both headsets in the remaining sessions.

The findings show that after using Auto Train Brain for 100 sessions with both headsets, the brain's flexibility—or its capacity to use new functional networks—increased. With 5-channel neurofeedback with Auto Train Brain, the amount of time and sessions needed to achieve brain flexibility is doubled. The brain can more quickly lateralize to the left thanks to 14-channel neurofeedback. The left hemisphere begins to dominate after the 20th session, and after some adjustments around the 60th session, the left hemisphere's dominance becomes permanent. Families who employ 14-channel neurofeedback might observe the benefits in the child's day-to-day activities much more quickly.

The frontal, parietal, and occipital lobes, as well as the temporal lobes, start developing new connections with one another as part of normal brain development. Results from a large-scale longitudinal healthy pediatric neuroimaging investigation revealed nonlinear changes in cortical gray matter, with an increase during preadolescence and a drop during adolescence for healthy individuals, whereas they confirmed linear increases in white matter. The frontal, parietal, and temporal lobes all reached their developmental peaks around the ages of 12 and 16, respectively, while the occipital lobe's cortical gray matter grew until age 20[39]. There were some regional variances in the cortical gray matter. The connections between the right and left hemispheres grow more secure as a child ages, and the left hemisphere starts to develop. After neurofeedback, we have realized that dyslexic children follow the normal growth path of the brain which increases the hypothesis of brain maturation delay.

Six dyslexic children were given neurofeedback by Nazari[50], who did not observe any significant changes in the power bands but did observe normalization of coherence in the theta band at T4-T4, delta band at Cz-Fz, and beta band at Cz-Pz, Cz-Fz, and Cz-C4. Hypo coherence is the symptom of disconnection syndrome. He has come to the conclusion that the increases in reading ability and phonological awareness are explained by the large changes in coherence, which point to the integration of sensory and motor domains.

Coben demonstrated that coherence neurofeedback raises reading scores for those with reading problems by 1.2-grade levels[51].

In the literature, fMRI has been used to demonstrate the increase in functional connectivity following fMRI-based functional connectivity neurofeedback[52]. To measure the improved functional connectivity[52] following coherence neurofeedback, coherence and phase lag on the EEG should be computed. It is challenging to do real-time coherence calculations using QEEG and EMOTIV headsets. Therefore, a suitable indicator of the in-session changes in functional connectivity networks is the variance of gamma band entropy across neurofeedback sessions.

It should be noted that neurofeedback does not cure the root cause of dyslexia. 14-channel neurofeedback may help the left lateralization of the brain which is one of the most dramatic changes in the healthy brain during its projection of

growth. The electrophysiological changes reflect cognition as shown by the prior research on Auto Train Brain[31]. Neurofeedback has unique advantages for affecting cognition, albeit indirectly[53].

The unexpected finding is that the gamma band entropy is not increased constantly. It varies from one session to another and there are pruning phases after 20-30 sessions.

The first limitation of the study is the possibility of placebo effects. As described by[54] children that are given one-on-one interactions and specialized interventions may improve their functioning based solely on the social and environmental impact of those interventions. Because no alternative intervention for the control group was provided, placebo effects may represent a significant source of improvement.

The second limitation of the study is the maturation effect as the experiment took 6 months.

The third limitation of the study is that it requires extensive effort to use EPOC-X at home for parents, but gives more insight related to the brain waves. The families may understand their child's situation better and take precautions better.

The fourth limitation is the number of participants. This is a pilot study that should be repeated with more participants in the near future.

For future research, we will investigate new calculation methods of coherence and functional connectivity based on QEEG and test our hypotheses with this calculation.

Conclusion

The variance of gamma band entropy changes over neurofeedback sessions presents promising results to explain electrophysiological changes and adaptations in the brain. Auto Train Brain was proven to be effective in improving reading comprehension and reading speed beforehand. Now, with the new calculation method, we have investigated the electrophysiological changes in the left temporal region after neurofeedback.

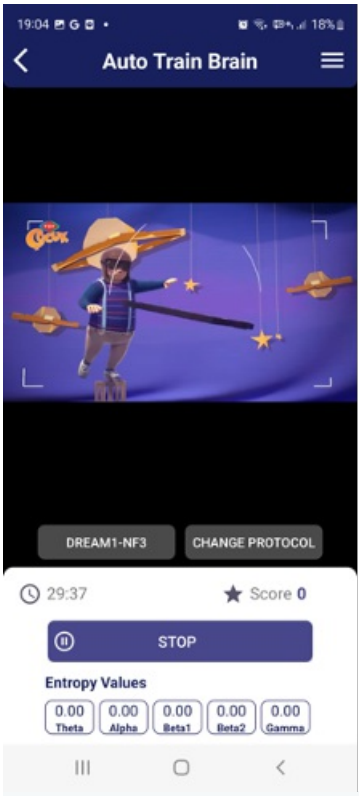

Figure 7. *Auto Train Brain "youtube" interface*

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