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Measuring the Gamma Band Entropy Variance is a Novel Method to Compare the Efficacy of Neurofeedback in the Left Temporal Region and in the right Temporal Region for Dyslexia: Pilot Study

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ABSTRACT

Purpose: The smartphone application called Auto Train Brain aims to improve reading comprehension and speed for people with dyslexia through neurofeedback. Clinical trials have been conducted to examine the efficacy of neurofeedback on dyslexia. However, accurately measuring long-term outcomes with rapidly changing electroencephalogram (EEG) data can be challenging without the use of psychometric tests. To overcome this issue, a novel measurement method was developed using the sample entropy variance calculated in the gamma band to compare different sessions.

Methods: 40 children with dyslexia aged 7 to 10 consisted of the experimental group that was randomly assigned and they used Auto Train Brain for six months.

Results: Results of the study showed that after 100 sessions, the 14-channel neurofeedback with Auto Train Brain was more effective in increasing the gamma band entropy variance in the left temporal lobe (T7) compared to that of the right temporal lobe (T8).

Conclusion: Using the measurement of gamma band entropy variance was identified as a suitable approach to assess the success of neurofeedback.

TİTÇK (Nbr: 71146310-511.06,2.11.2018)

Keywords: Neurofeedback, entropy, learning disorders, dyslexia, EEG.

ÖZET

Amaç: Auto Train Brain adlı akıllı telefon uygulaması, disleksi olan kişilerin okuduğunu anlama ve okuma hızını nörogeribildirim yoluyla artırmayı amaçlamaktadır. Disleksi üzerindeki nörogeribildirim etkinliğini incelemek için klinik deneyler yapılmıştır. Ancak, hızla değişen elektroensefalogram (EEG) verileriyle uzun vadeli sonuçları doğru bir şekilde ölçmek, psikometrik testler kullanılmadan zor olabilir. Bu sorunu aşmak için, farklı seansları karşılaştırmak amacıyla gama bandında hesaplanan örnek entropi varyansı kullanılarak yeni bir ölçüm yöntemi geliştirilmiştir.

Metodlar: 7 ile 10 yaşları arasında disleksi olan 40 çocuk deney grubunu oluşturdu ve rastgele atanarak altı ay boyunca Auto Train Brain kullandılar.

Sonuçlar: Çalışmanın sonuçları, 100 seans sonrasında Auto Train Brain ile yapılan 14 kanallı nörogeribildirimin, sol temporal lobdaki (T7) gama bandı entropi varyansını sağ temporal loba (T8) göre artırmada daha etkili olduğunu gösterdi.

Özet: Gama bandı entropi varyansının ölçülmesi, nörogeribildirim başarısını değerlendirmek için uygun bir yaklaşım olarak bulunmuştur.

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Anahtar Kelimeler: Nörogeribildirim, entropi, öğrenme bozuklukları, disleksi, EEG.

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Dyslexia is a subcategory of Specific learning disorders according to Diagnostic and Statistical Manual of Mental Disorders (DSM) V criteria (1). Some people struggle with reading, despite having Intelligence Quotients (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). According to (5), dyslexia is distinguished by significant under activity in the reading network, disturbed functional connections, and variations in structural connections in specific fiber tracts.

Even if children with dyslexia receive the necessary supportive education and adequate nutrition, it takes a very long time to close the gap between their peers (6). 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 working memory, and to quickly retrieve phonological representations from the long-term memory (6).

It is hypothesized that there is a disconnection syndrome in the left temporal lobe of dyslexia (7). The slow brain waves in the left temporal region are increased for dyslexia (8) 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 (9).

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 (10).

Studies have indicated that dyslexic children have slow brain waves at the left frontal, and do not exhibit beta-1 activity desynchronization while performing reading tasks in regions associated with the Angular gyrus, the Broca region, and the left parieto-occipital region have an important role in semantics and mathematics comprehension (11), while the right temporal and parietal areas exhibit elevated sluggish activity (12,13). According to researchers, there is a disruption in the left temporal region (14). Furthermore, individuals with dyslexia and Attention-Deficit/Hyperactivity Disorder (ADHD) may experience high levels of frontal sluggish activity and increased coherence in the delta and theta bands symmetrically at temporal regions, while the alpha and beta bands show a distinct right-temporal central increase in coherence (13). Bi-hemispheric hyper-coherence (between T3 and T4) is observed in the delta and theta bands, whereas hypo-coherence in the delta, theta, and alpha bands is present between P7 and O1. Dyslexia is also associated with gamma band issues and less functional connections, with the left and right temporal lobes being the sources of healthy functional connections. (15,16).

Neurofeedback has been established as a technique that can improve the consequences of dyslexia by allowing the subject to gain more control over their brain through operant conditioning (17). This phenomenon has been shown to add weak connections that can help the subject pay attention and learn better when they learn to manage a specific brain area (18). The American Psychological Association (APA) recognizes neurofeedback as a "possibly efficacious" technique (19). While demonstrating the effectiveness of neurofeedback can be challenging, clinical studies have shown advancements in psychometric tests used before and after the investigation (20). Furthermore, several studies have shown that neurofeedback leads to improvements in brain structure, including improved functional connectivity of the sensorimotor resting state network and increased fractional anisotropy (FA) in the corpus callosum after one hour of Neurofeedback (NFB) training. The default mode network also showed increased functional connectivity (21). While functional Magnetic Resonance Imaging (fMRI) is typically used in these studies to display strongly linked brain regions following neurofeedback, it is challenging to demonstrate changes in the brain using Quantitative electroencephalography (QEEG). However, research has shown a causal relationship between neurofeedback and cognitive improvement (22-25).

Auto Train Brain contains modules of multi-channel neurofeedback, multimodal learning, and special education principles (26). It also contains dyslexia biomarker software which is built with Machine Learning (ML) methods.

In this research, we have compared the gamma band entropy variance in the temporal lobes during 14-channel neurofeedback for dyslexia with Auto Train. Due to the challenges of measuring long-term results with rapidly changing EEG data, a new measurement method was developed using the sample entropy variance in the gamma band.

Materials and Methods

A. Subjects

40 children with dyslexia (aged 7 to 10, 34 males, 6 females) participated in the experiments providing their written consent. They have used Auto Train 100 times to improve their reading abilities for 6 months.

The children in the experimental group were diagnosed with dyslexia by psychiatric professionals, who then recommended using Auto Train Brain. The Test of Integrated Language & Literacy Skills (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 socioeconomic position survey was conducted among parents of children, wherein questions related to their employment, education (primary, secondary, and tertiary), and income were asked. The income categories were defined as follows: low income (< 6,000 TL), middle income (6,000 TL to 20,000 TL), and high income (> 20,000 TL). The participants' occupation was categorized into three groups: white-collar, blue-collar, and staff.

B. Qeeg Recording

The experiments utilized EMOTIV EPOC-X headsets to gather data from 14 channels: AF3, F3, F7, FC5, T7, P7, O1, O2, P8, T8, FC6, F8, F4, and AF4. The EEG data was captured at 2048 samples per second per channel, then downsampled to 128 samples per second per channel. The raw EEG data was transformed to the frequency band using Fast Fourier Transform (FFT). A low pass filter (<100Hz) and high pass filter (4Hz) were used to eliminate noise. The frequency band was then classified into Theta (4-8 Hz), Alpha (8-12 Hz), Beta-1 (12-16 Hz), Beta-2 (16-25 Hz), and Gamma (25-45 Hz). Calibration was performed using EMOTIV LAUNCHER to ensure high-quality EEG data was collected from each electrode. The EMOTIV EPOC-X, a commercially available wearable EEG device, was utilized. It has 14 sensors, felt pads, and two rubber electrodes were placed in the mastoids following the International 10-20 system. The electrodes were connected to the scalp using saline liquid solution. The sampling frequency was 128 Hz.

C. Auto Train Brain Patented Neurofeedback Protocol

The Auto Train Brain mobile application uses the EMOTIV EPOC-X headset and employs principles of neurofeedback to improve brain performance in both children and adults. The system real-time online reads QEEG signals from 14 channels, processes them, and delivers real-time visual and auditory online neurofeedback. The unique protocol of multi-sensory learning and EEG neurofeedback aims to improve reading ability and cognitive functions. It reduces the theta waves in the Broca and Wernicke areas of the brain if they exceed the threshold, identifying channels with the highest absolute power of theta waves in each hemisphere, and reducing absolute theta for those channels. Feedback is provided through green and red arrows on the screen, and a "beep" sound to indicate positive and negative feedback, respectively. Auto Train Brain stands out from other neurofeedback systems because it combines neurofeedback with multi-sensory learning principles.

D. Study Design

Forty participants, aged between 7 and 10 years, utilized the Auto Train Brain mobile phone application for over 100 sessions. During each session, their brain waves were monitored using the EMOTIV EPOC-X headset for 14 channels and were given visual and auditory neurofeedback for 30 minutes. Following the neurofeedback session, the participants engaged in a 15-minute multi-sensory alphabet learning study.

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.

Upon completion of each session, the session average data for every frequency band was saved to the database. Additionally, sample entropy was computed for the data of each frequency band during the neurofeedback session. (12).

E. Variance of Sample Entropy for Gamma Band as the Measure

Sample entropy is a complexity measure used to evaluate physiological time-series signals and identify disease states. It is represented by SampEn(m, r, N), which is the negative natural logarithm of the probability that two sets of simultaneous data points of length m and m+1 have distances less than a given tolerance r, given an embedding dimension of m and a number of data points of N.

Variance, on the other hand, is a dispersion measure that represents the expected value of the squared deviation of a random variable from its population or sample means. It reflects how far a set of numbers deviates from their average value.

For every session, the sample entropy of the gamma band frequency is computed and saved. The gamma band entropy variances is then calculated for a group of sessions. Although sample entropy is typically calculated based on EEG data series, we used QEEG data for our computations since we lacked access to the raw data from the EMOTIV EPOC-X. The feature set comprises 14 variables containing gamma band values mapped from the 14 channels of the EMOTIV EPOC-X. Finally, the sample entropy variance in the gamma band is measured for each group of activities.

F. 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 gamma band entropy variance (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 gamma band entropy variance(y-axis) in the left (T7) and right temporal(T8) regions versus session groups (x-axis)).

Results

A regression statistical method is applied to the two-dimensional data (session numbers versus the sample entropy variance). The findings suggest that long-term neurofeedback use increased the gamma band sample entropy variance.

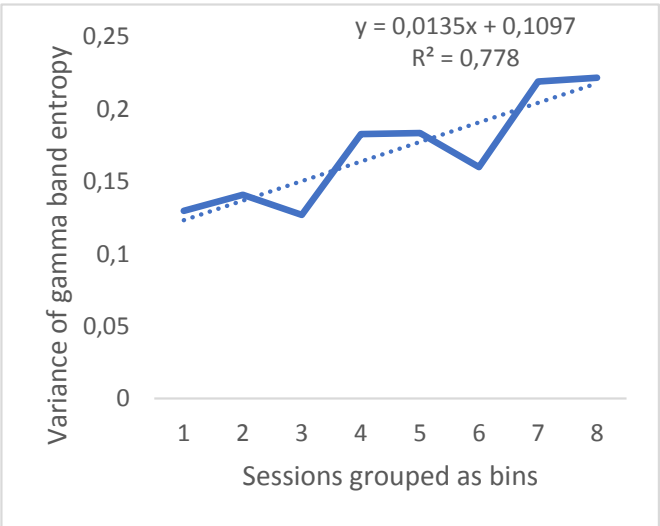

Figure 1: The increase in the gamma band entropy variance (y-axis) y in the left posterior region after 30 sessions (x-axis, 1 bin=10 sessions) for a 14-channel EEG headset

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 sample entropy values' bin number vs variance. In both headsets' left posterior regions, the sample entropy variance in the gamma band rose over time (T7).

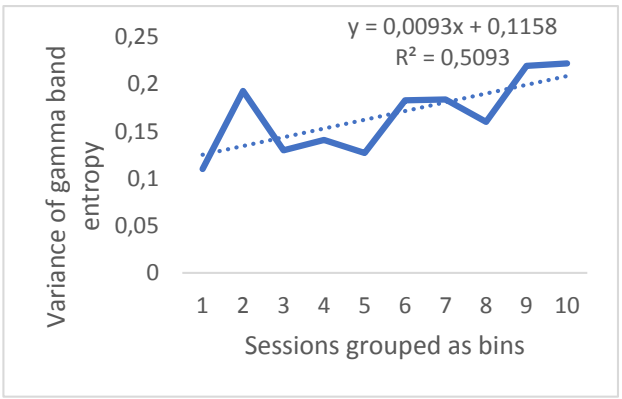

Figure 2: The change in the gamma band entropy variance (y-axis) in the left temporal region for a 14-channel EEG headset in the 100 sessions (x-axis, 1 bin= 10 sessions)

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 I). 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 II). In both instances, the linear regression lines' slopes were upward statistically significantly.

For a 14-channel headset, the gamma band entropy variance changes in the left temporal and the right temporal regions in the 100 sessions are plotted in Figure III.

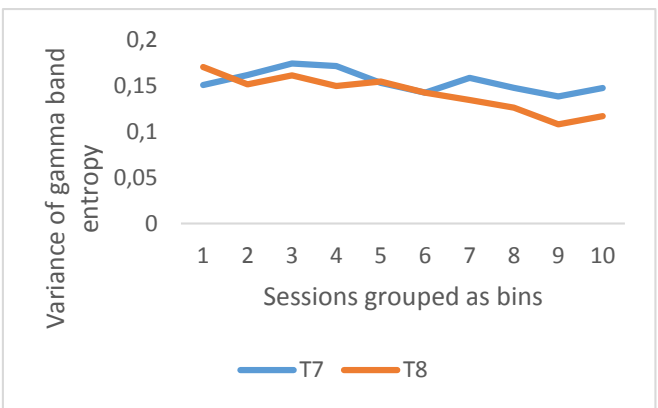

Figure 3: The change in the gamma band entropy variance (y-axis) in the left (T7) and right temporal(T8) regions for a 14-channel EEG headset in the next 100 sessions (x-axis, 1 bin=10 sessions)

Figure III shows that at around 20th sessions, the gamma band entropy variance becomes permanently dominant for the left temporal region after 60 sessions [$F_{(1, 6)}$ = 20.79, p=.0038]. Figure IV shows the user interface of Auto Train Brain.

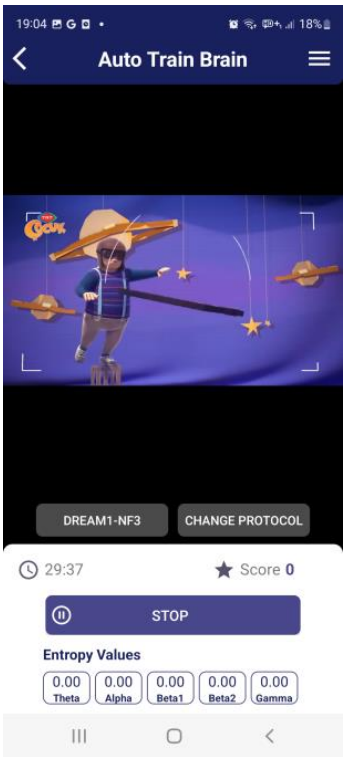

Figure 4: Auto Train Brain "youtube" interface

As the participant's ages were 7-10 years old, the result is generalizable to 7-10-year-old children with dyslexia only.

Discussion

This research is unique in its approach to measuring the long-term outcomes of neurofeedback using a novel measurement method. While clinical trials have been conducted to examine the efficacy of neurofeedback on dyslexia, the use of the sample entropy variance calculated in the gamma band to compare different sessions is a unique approach. Additionally, the focus on the left temporal lobe (T7) compared to the right temporal lobe (T8) is a specific aspect that sets this research apart from previous studies.

In the first 20 sessions of use, 14-channel neurofeedback in the left posterior region causes a sharp increase in the sample entropy variance in the gamma band. The sample entropy variance in the gamma band is reduced after the 20 sessions for 14-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 gamma band entropy variance. There are two further steps of pruning for both headsets in the remaining sessions. Moreover, the sample entropy variance in the left temporal lobe becomes dominant after 60 sessions of usage.

In a prior clinical study that assessed the efficacy of Auto Train Brain for children with dyslexia (26), pre- and post-TILLS test comparisons were conducted. The experimental group demonstrated a substantial increase in reading speed, from 38 to 65, following the 60-session clinical trial. Moreover, compared to the control group that received special education, the experimental group exhibited a statistically significant improvement ($p = .042$) in reading comprehension. Further posthoc tests indicated that the training with Auto Train Brain led to a noteworthy enhancement in reading comprehension (26).

According to Wu's research (27), neural stability plays a crucial role in supporting behavioral stability and reading automaticity. Nazari (28) administered neurofeedback to six dyslexic children and noted a normalization of coherence in the theta band at temporal, delta band at the frontocental, and beta band at central electrodes, despite no significant changes in the power bands. Hypo coherence, indicating a disconnection syndrome, was observed. The author suggests that the significant improvement in reading ability and phonological awareness is attributable to the substantial changes in coherence, indicating the integration of sensory and motor domains. Coherence neurofeedback, as demonstrated by Coben (29), can raise reading scores by 1.2-grade levels for individuals with reading problems. fMRI has been utilized in the literature to show an increase in functional connectivity after neurofeedback (29). In order to assess the enhanced functional connectivity after coherence neurofeedback, it is necessary to compute the coherence and phase lag on the EEG. Nevertheless, performing real-time coherence calculations utilizing QEEG and EMOTIV headsets is difficult. Therefore, the gamma band entropy variance throughout the neurofeedback sessions is a suitable indicator of the changes in functional connectivity networks during the sessions.

This study has several limitations that need to be considered. Firstly, placebo effects could be a factor, where children receiving specialized interventions may exhibit improved functioning simply due to those interventions' social and environmental impact. Secondly, the experiment spanned over 6 months, which could introduce a maturation effect. Thirdly, the number of participants was limited, given that this was a pilot study, and further research with a larger cohort is warranted. Lastly, the absence of a control group is another limitation of the study.

For future research, we will investigate new calculation methods of coherence and functional connectivity based on QEEG and test our hypotheses with this calculation. The gamma band entropy variance over neurofeedback sessions presents promising results to explain electrophysiological changes and adaptations in the brain. Auto Train Brain has high efficacy 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 compared with the right temporal region after neurofeedback efficiently.

Conclusion

Accurately measuring long-term outcomes with rapidly changing electroencephalogram (EEG) data can be challenging without the use of psychometric tests. To overcome this issue, a novel measurement method was developed using the sample entropy variance calculated in the gamma band to compare different sessions. Using the measurement of gamma band entropy variance was identified as a suitable approach to assess the success of neurofeedback.

Declarations

Funding

None

Conflicts Of Interests

The author declares the following financial interests which may be considered as potential competing interests. Auto Train Brain has been developed at Sabancı University laboratories. This work has led to the formation of a company aimed to make Auto Train Brain available to users (www.autotrainbrain.com).

Ethical Approval

After the experimental procedure was explained to them following the guidelines established by the research ethics committee, all participants provided their informed consent. Yeditepe University Ethics Committee approved it, and the clinical trial was registered with the TİTÇK (Nbr: 71146310-511.06,2.11.2018).

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Availability of Data and the Material

Upon a reasonable request, the datasets generated and/or analyzed during the current study will be provided by the corresponding author.

Authors Contributions

GE has written the whole manuscript by herself.

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