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ON THE COMPLEXITY AND ENERGY ANALYSES IN EEG BETWEEN ALCOHOLIC AND CONTROL SUBJECTS DURING DELAYED MATCHING TO SAMPLE PARADIGM

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In this study, we have investigated the electrophysiological differences between alcoholic and control subjects using two different approaches namely complexity and energy (power) analyses. The electroencephalogram data used in this study were recorded from 77 alcoholic and 44 control subjects while the subjects were performing delayed matching to sample object recognition task for three types of stimuli. These were a single stimulus and a second matching or nonmatching stimulus that followed the single stimulus after a delay. The experimental paradigm evokes object recognition, visual short-term memory, and decision-making abilities. The results indicated that all regions (i.e. frontal, central, temporal, parietal, and occipital) in the brain exhibit more complexity and less energy for alcoholic subjects as compared to controls. When different visual stimuli pairs were compared among alcoholic and control subjects, the results from energy analysis showed groupwise differences in occipital and parietal regions. These results provide a strong indication on the impairment in brain's electrophysiological activity for alcoholic subjects due to a history of long-term alcohol abuse.

Keywords: Alcohol abuse; electroencephalogram; energy analysis; nonlinear complexity.

1. Introduction

Addiction based diseases are the major cause of concern in the society. Among these addiction based diseases, alcohol related health disorders are the most frequent. It is known that even moderate alcohol consumption leads to short-term memory impairments and blackouts. These impairments could cause accidents in some jobs such as drivers, pilots, and machinery operators since it is critical to make fast and correct decisions. Therefore, it is important to investigate whether long-term alcohol abuse has permanent effect on memory, attention, and decision making.

In recent years, considerable research has been done to investigate the effects of long-term alcohol abuse on the brain. Literature reviews have shown that heavy

drinking may have large scale effects ranging from short-term memory loss to blackouts in some of the alcoholics.[1]

Electroencephalogram (EEG) is a representative signal that contains useful information about the electrical activity of the brain. Due to its noninvasive nature, the analysis of EEG signals has become increasingly attractive in recent years (i.e. for neurophysiological studies and clinical purposes). One of the most important applications using EEG is analysis of brain electrical activity under various conditions such as sleep disorders, epilepsy, mania, and depression.[2] In this paper, we have utilized Visual Evoked Potential (VEP) signals, which is a type of Event Related Potential (ERP) that is evoked by external visual stimulus, for investigating the electrophysiological differences between alcoholic and control (nonalcoholic) subjects during delayed matching to sample paradigm. Note that ERP is the evoked component in the EEG signals in response to an external stimulus such as visual, auditory or somatosensory.

Previous research studies using EEG and VEP signals have shown that the brain activity of alcoholic and control subjects differs in numerous aspects.[1,3−9] In particular, when considering the difference in event related potentials between alcoholics and nonalcoholics, these researchers focused on several ERP components such as c240 and c320,[1] P300,[4−7,10] N400,[4,5] contingent negative variation (CNV), and mismatch negativity (MMN).[5] However, there has been no reported study that compared complexity or energy of brain signals of alcoholics evoked during delayed matching to sample paradigm.

In this study, we set out to analyze the complexity and energy of VEP signals obtained from alcoholic and control subjects. In the study by Natarajan *et al.*,[11] it was suggested that using nonlinear measures would be a better approach for the complexity analysis of brain signals since these signals exhibit irregular behavior with nonlinear dynamical properties. As such, we have utilized Approximate Entropy (ApEn), which is a commonly used nonlinear measure of complexity. Using complexity and energy analysis approaches, we set out to show that there are significant electrophysiological differences between alcoholics and controls.

2. Methodology

2.1. *Subjects*

The EEG signals used in this study were recorded from 121 male subjects where 77 of the subjects were alcoholics and the rest were control subjects. The mean age of the alcoholic group was 35.83 years with SD = 5.33 ranging from 22.33 to 49.8 years old while the mean age of control group was 25.81 years old with SD = 3.38 ranging from 19.4 to 38.6 years old. The alcoholic subjects were significantly older than the control subjects [$t(118.9) = 12.64$, $p = 0.0001$].

In the paper by Rourke *et al.*,[9] the effects of age and length of abstinence on the recovery of neuropsychological functioning in male alcoholics have been discussed.

According to their results, both recently detoxified and alcoholics that have been sober for 2 years and who were older than 50 years of age performed worse on visual recall compared to similarly aged long-term abstinent alcoholics and nonalcoholic subjects, on the other hand all the participants less than 50 years of age performed at comparable levels. In this study, all of the subjects were younger than 50 years old so we did not employ analyses of covariance controlling for age.

Most of the alcoholic subjects had been drinking heavily for 15 years, starting approximately at the age of 20. The diagnosis of alcohol dependence was made by the intake of the addictive disease hospital in Brooklyn according to DSM-III criteria. The alcoholic subjects had not been drinking and taking any medication for a minimum of one month, therefore all of them were fully detoxified during that period of time. The alcoholic subjects that had a history of overt liver, metabolic, vascular, and neurological diseases, major psychiatric illness or drug dependence were excluded from the study.

The control subjects had no personal or family histories of alcohol or drug dependence and the ones having any history of neurological or major psychiatric illness were excluded from the study.

All subjects had normal vision or corrected normal vision.

2.2. *Mental task*

In this study, the subjects were exposed to two consecutive visual stimuli. The visual stimuli were pictures of objects selected from Snodgrass and Vanderwart picture set.[12] These pictures were common black and white line pictures which can be recognized easily by all subjects such as banana, kite, aeroplane, ball, bicycle, etc. These simple pictures were used to avoid possible ambiguity since some amnesic subjects cannot recognize complex pictures easily.[13] Figure 1 shows some examples of Snodgrass and Vanderwart pictures.

In order to preserve the consistency of the representation of the pictures, the pictures were grouped into different categories according to their semantic category

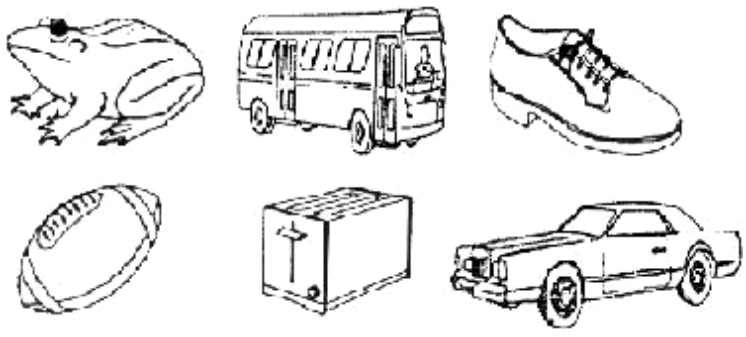

Fig. 1. Some examples from Snodgrass and Vanderwart picture set.

within the brain such as four footed animal, fruit, weapon, musical instrument, etc. The pictures were presented such that if the first visual stimulus is from one group, the second visual stimulus will be from another group.

2.3. *Subjects' task*

The task assigned to the subjects was to decide whether the first and the second pictures presented to them were matching or nonmatching. The subjects were asked to press a mouse key in one hand if the pictures were same and press a mouse key in the other hand if the pictures were different. The selection of the hand indicating the matching and nonmatching was altered between subjects.

2.4. *Recording*

The subjects were seated in a reclining chair located in a sound proof, RF shielded room during the recording session. The EEG signals were recorded for one second from 64 electrodes placed on the scalp of the subject and were sampled at 256 Hz. Therefore, a total of 256 data points were stored for each EEG signal from every channel (electrode). The electrode placement system used was an extension

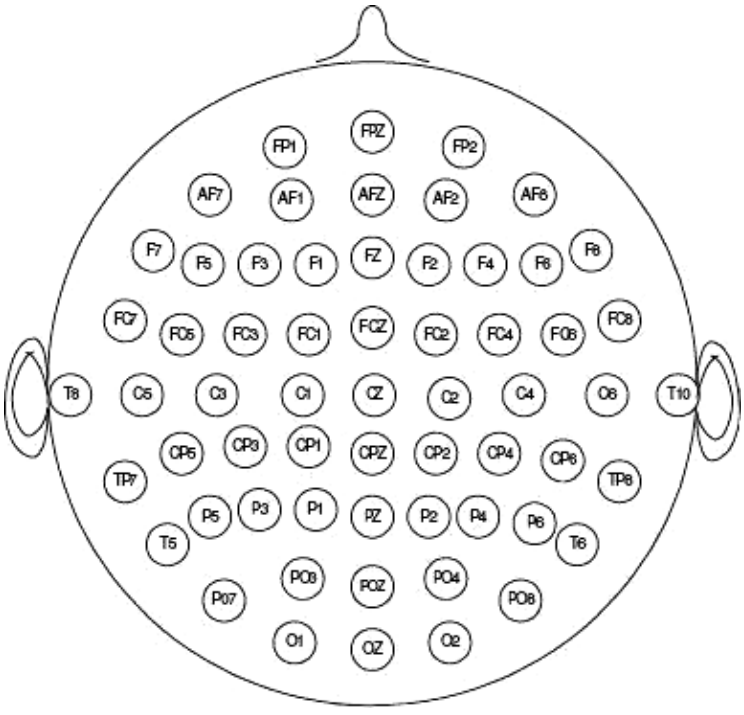

Fig. 2. 61 Channel electrode system.

of the 10–20 international electrode positioning system.[14] International 10–20 system contains 19 active channels and two reference channels whereas the extension has 61 active channels plus three reference channels. The positions of the active 61 channels are as shown in Fig. 2.

For performing regional comparison between the two groups of subjects (i.e. alcoholics and controls), the channels were used to create vector sets belonging to each region. The channels are organized such that the frontal region consisted of Fp1, Fpz, Fp2, Af7, Af8, Af1, Af2, Afz, F7, F8, F5, F6, F3, F4, F1, F2, and Fz. The central region consisted of Fc1, Fc2, Fc3, Fc4, Fc5, Fc6, Fc7, Fc8, Fcz, C1, C2, C3, C4, C5, C6, and Cz. The parietal region consisted of Cp1, Cp2, Cp3, Cp4, Cp5, Cp6, Cpz, P1, P2, P3, P4, P5, P6, and Pz. The occipital region consisted of Po1, Po2, Po7, Po8, Poz, O1, O2, and Oz. The temporal region consisted of T8, T10, Tp7, Tp8, P7, and P8. These selections of channels were obtained from a previous study.[1]

The recording of EEG was done when the subjects were performing object recognition task as explained in the previous section. The subjects were exposed to the first visual stimuli (S1) for 300 ms. After an interval of 1.6 s, the subjects were exposed to a second visual stimulus for another 300ms which could be either in matching (S2M) or nonmatching (S2N) condition. The duration between each trial was 3.2 s. This paradigm is known as the delayed matching to sample paradigm.[3] Figure 3 shows an example of the visual stimulus presentation for the case of S2N.

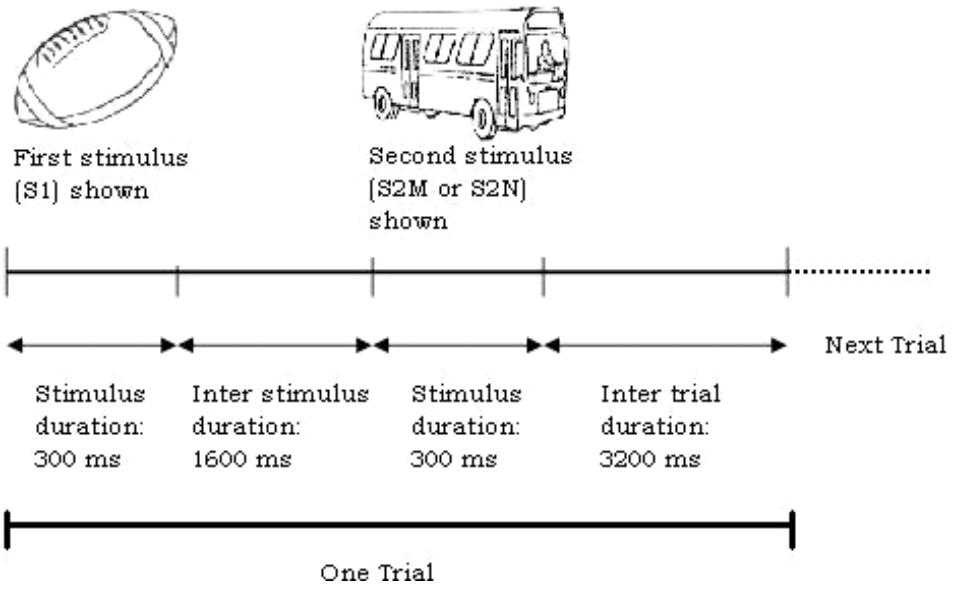

Fig. 3. An example of visual stimulus presentation in the case of S2N.

2.5. *Subjects' performances on tasks*

Both groups of subjects had a low response error rate for performing the task. There were no significant differences in response errors in matching and nonmatching trials within the groups but alcoholic subjects made more errors in matching and nonmatching trials than control subjects as shown in Table 1.

Furthermore the stimulus condition had a significant effect on response times of subjects where the response time to matching stimulus was significantly shorter than nonmatching stimulus in both of the groups. Besides, in both of the stimulus conditions the alcoholic subjects had a longer response time than controls as shown in Table 2.

2.6. *Pre-processing*

In the pre-processing stage, EEG signals were first hardware (analogue) band-pass filtered between 0.002 and 50 Hz, this is a common place to practice in practical EEG data manipulation. After that, the EEG signals were decimated by a factor of two to reduce the effective sampling frequency to 128 Hz. Aliasing effects will not be a problem as the EEG signals were low pass filtered to 50 Hz earlier.

In the next step, eye-blink artifact contaminated EEG signals were detected and removed from the records based on amplitude discrimination. This was achieved using a computer program written to detect EEG signals in frontal and prefrontal regions with magnitudes above 100 μV. The value of 100 μV was selected since blinking produces a potential of 100–200 μV lasting for 250 ms.[19]

After removing the eye-blink contaminated signals, VEP component (which is related to the stimulus) was extracted from the EEG signal. Basically the VEP component is hidden in EEG signals and the amplitude of EEG that is not related to the stimulus is much higher than the VEP component. Since we are interested in VEP only, ensemble averaging was performed to and obtain VEP component hidden in the EEG signals. We had a total of 5,497 EEG signals for first visual stimulus,

Table 1. The response errors during performance of mental tasks.

	Matching Stimulus (Mean ± SD)	Nonmatching Stimulus (Mean ± SD)
Alcoholic subjects	0.62 ± 1.11	0.39 ± 0.78
Control subjects	0.29 ± 0.59	0.12 ± 0.31

Table 2. The response times(ms) during performance of mental tasks.

	Matching Stimulus (Mean ± SD)	Nonmatching Stimulus (Mean ± SD)
Alcoholic subjects	608.6 ± 90.32	678.6 ± 90.10
Control subjects	575.7 ± 109.8	644.1 ± 107.1

2,777 EEG signals for the second matching visual stimulus and 2,720 EEG signals for second nonmatching visual stimulus belonging to 77 alcoholic and 44 control subjects. The number of trials was not the same for each subject where there was a minimum of 10 and a maximum of 50 trials from each subject. As mentioned before the VEP signals are extracted by averaging the multi-trial EEG signals from each subject. Upon the completion of this step, we had a total of 64 channels of VEP for each S1, S2M, and S2N stimulus belonging to 77 alcoholic subjects and similarly 64 channels of VEP for each S1, S2M, and S2N stimulus belonging to 44 control subjects. Note that three channels were reference ones, hence only the active 61 channels were used from the recorded 64 channels.

2.7. *Data analysis*

For analyzing the electrophysiological damages caused by long-term alcohol abuse, we used two different approaches in this study; namely complexity and energy analyses of the VEP signals.

2.7.1. *Complexity analysis using approximate entropy*

In this first approach, our aim was to compare the complexity in VEP from each region between alcoholic and control subjects. The complexity analysis can provide insight to the condition of the brain of alcoholic subjects. There are many ways of analyzing the complexity of VEP signals namely the linear measures such as global field strength (Σ), global frequency field changes (Φ) and spatial complexity (Ω)[15] and nonlinear measures such as ApEn, Hurst Exponent, Largest Lyapunov Exponent, and Correlation Dimension.[11]

Previously it has been shown that the electrical activity of the brain exhibits complex behavior with nonlinear dynamical properties.[11] Considering this fact, Natarajan *et al.*[11] suggested that using nonlinear measures would be a better approach than traditional linear methods for analyzing the complexity of brain signals. Hence, in this study, we focused on the commonly used nonlinear measure of complexity namely the ApEn.

ApEn is a recently developed method that measures the irregularity of a signal in time.[15] In other words, if a data point of a signal can be predicted accurately using the previous points of the signal, then the signal is considered as regular; whereas if the point cannot be predicted accurately, then the signal is considered as irregular.

The measure of irregularity of the signal in time is obtained by comparing the original time series with time shifted versions of itself namely embedding the signal in phase space. The number of previous points used in making the prediction of the next data point is the embedding dimension, m.

Before ApEn can be computed, two parameters must be determined; these are the embedding dimension, m and radial distance, r which is the tolerance of the measure namely noise threshold. For this study, the value of m is set to 2 and r is

set to 15% of the standard deviation of VEP signal since it is reported that these values provide good statistical validity for ApEn.[15]

The first step for estimating the ApEn of a time series is calculating the correlation integral of time series. Assuming that we have the VEP signal from one channel, $x = x(t), x(t+\tau), \ldots, x(t+(N-1)\tau)$, which has N data points that are measured with intervals of τ, a sequence of vectors using time delay embedding, with dimension m, must be constructed such that; $y(t) = x(t), x(t+\tau), x(t+2\cdot\tau), \ldots, x(t+(m-1)\cdot\tau)$. Following this, the distance between all pairwise vectors $y(i), y(j)$ must be determined such that $i, j = 1, \ldots, N-(m-1)$. After that the correlation integral can be calculated by

$$C_i^m(r) = \sum_{i}^{N-(m-1)} \sum_{j=i+1}^{N-(m-1)} \Theta(r - d[y(i) - y(j)]), \tag{1}$$

where $\boldsymbol{N}$ is the length of signal, $\boldsymbol{r}$ is the tolerance of the comparison, $\boldsymbol{y(i)}$ is the vector in embedding space constructed from the signal, $\boldsymbol{d[y(i), y(j)]}$ is the Euclidean distance between vectors, $y(i)$ and $y(j)$, $\boldsymbol{\Theta(x)}$ is the Heaviside function such that $\Theta(x) = 1$ if $x > 0$ and $\Theta(x) = 0$ if $x < 0$.

After the calculation of correlation integral the ApEn(m, r, N) is obtained by

$$ApEn(m, r, N) = \Phi^m(r) - \Phi^{m+1}(r), \tag{2}$$

where

$$\Phi^m(r) = \frac{1}{N-(m-1)} \sum_{i}^{N-(m-1)} ln[C_i^m(r)], \tag{3}$$

with $\boldsymbol{C(x)}$ as the correlation integral.

2.7.2. *Energy analysis*

In the second part of the analysis, we have computed energy from each channel to compare the VEP energy (power) differences between alcoholics and controls. The energy of each VEP signal is calculated using the equation below:

$$Energy = \sum_{n=1}^{N} [x(n)]^2, \tag{4}$$

where $\boldsymbol{N}$ is the total number of data points and $\boldsymbol{x(n)}$ is the data at sampled point n.

3. Experimental Results

In this section, the experimental results obtained by performing nonlinear complexity and energy analyses on the VEP signals will be presented.

3.1. *Complexity analysis*

The complexity of a signal gives information about the number of parallel processes running in the brain. The increased complexity suggests that there are more parallel processes in the brain (i.e. more level of difficulty) whereas the decreased complexity means that the brain is in a more focused state and there are less parallel processes in the brain.

In this part of the study, our aim is to show that there are regionwise differences in complexity between alcoholic and control subjects. For the comparison of the complexity values from two groups of subjects (i.e. alcoholics vs. controls) we generated the null hypothesis that the complexity values of each group are similar (i.e. the complexity values are drawn from the same population) and we performed the statistical analysis according to that null hypothesis. Initially, we analyzed the differences between alcoholics and controls for each picture stimulus (i.e. S1, S2M, and S2N). Then, we analyzed the pairwise differences of picture stimuli (i.e. the differences between S1 and S2M, S1 and S2N, S2M and S2N) among alcoholics and controls.

3.1.1. *Comparison of stimulus differences between alcoholic and control subjects*

We performed a multivariate analysis of variance (MANOVA) to compare the regionwise complexity differences using complexity values from each region as dependent vector. All the statistical comparisons were conducted at a confidence level of 95% (i.e. alpha was set 0.05). The p-values smaller than or equal to 0.05 indicated that the probability that the complexity values are drawn from the same population is very small. The test, therefore supported the alternate hypothesis that there were significant differences between two groups of subjects.

Table 3 shows the results of the regionwise complexity comparison between two groups of subjects. For both S1 and S2M stimuli, the complexities in all regions were significantly different between alcoholics and controls where the VEP signals of alcoholics exhibited higher complexity compared to controls. This could mean that when the alcoholics were exposed to the visual stimuli, they had to utilize more parallel processes in their brain to process the visual stimuli as compared to

Table 3. Complexity comparison between alcoholic and control subjects using approximate entropy method.

	S1 Picture Stimulus		S2M Picture Stimulus		S2N Picture Stimulus	
Region	Hypothesis	p-value	Hypothesis	p-value	Hypothesis	p-value
Frontal	1	0.00	1	0.03	0	0.43
Temporal	1	0.00	1	0.00	1	0.00
Central	1	0.00	1	0.05	1	0.04
Occipital	1	0.00	1	0.04	1	0.02
Parietal	1	0.00	1	0.00	1	0.00

control subjects. The increased complexity could be the reason of the slower and poorer quality of responses from alcoholic subjects, which were indicated in another study.[1]

For S2N stimulus, the regions: temporal, parietal, occipital, and central, exhibited significant difference whereas the frontal region did not indicate any significant difference between alcoholic and control subjects. The possible reason for this could be that the S2N stimulus evokes considerable decision-making ability when compared to the short-term memory recall, therefore the frontal region (which mediates mostly short-term memory) may have not evoked enough complexity to differentiate the groups during S2N stimulus; thereby indicating no significant difference in frontal region.

3.1.2. *Pairwise stimuli difference among control and alcoholic subjects*

We performed several MANOVA tests among control and alcoholic subjects to compare complexity values evoked by different stimulus conditions, i.e. S1 and S2M, S1 and S2N, S2M and S2N. Similar to the previous case, the statistical comparisons were conducted with a confidence level of 95% where p-values smaller than or equal to 0.05 indicated that there were significant differences between two groups of stimulus conditions.

Table 4. Complexity comparison of picture stimulus among alcoholic and control subjects using approximate entropy method.

	Alcoholic Subjects		Control Subjects	
	S1&S2M Picture Stimulus		S1&S2M Picture Stimulus	
Region	Hypothesis	p-value	Hypothesis	p-value
Frontal	1	0.01	1	0.05
Temporal	1	0.01	1	0.01
Central	1	0.00	1	0.00
Occipital	0	0.38	0	0.56
Parietal	0	0.52	0	0.19
	S1&S2N Picture Stimulus		S1&S2N Picture Stimulus	
Region	Hypothesis	p-value	Hypothesis	p-value
Frontal	0	0.12	0	0.19
Temporal	0	0.34	0	0.20
Central	1	0.00	1	0.00
Occipital	0	0.27	0	0.66
Parietal	0	0.96	0	0.68
	S2M&S2N Picture Stimulus		S2M&S2N Picture Stimulus	
Region	Hypothesis	p-value	Hypothesis	p-value
Frontal	0	0.68	0	0.97
Temporal	0	0.18	0	0.55
Central	0	0.87	0	0.53
Occipital	0	0.98	0	0.68
Parietal	0	0.89	0	0.69

Table 4 shows the results of comparison among control and alcoholic subjects using ApEn. As it could be seen from the table, region differences were similar among alcoholic and control subjects for all of the stimuli pairs.

When the subjects were exposed to S1, recognition and memory encoding takes place whereas when they were exposed to the S2M or S2N, memory access and decision-making processes are evoked. Both groups of subjects indicated significantly higher complexity for S2M as compared to S1 in frontal, temporal, and central regions. This denotes more complexity in these regions during memory retrieving and comparing the matching stimulus. When the subjects were exposed to S2N, only the central region indicated higher complexity which could denote that nonmatching stimulus (being easier to decide the mismatch and in some manners, similar to S1 like seeing a new picture) does not involve more complexity in most parts of the brain as compared to S1. When S2M and S2N were compared, the results indicated no differences in any region since these cognitive processes evoke similar amount of complexity.

3.2. *Energy analysis*

In the second part of the analysis, energy (power) of the VEP signals between alcoholics and controls were compared. Similar to complexity analysis, we initially compared the picture stimulus (i.e. S1, S2M, S2N) energy differences between alcoholic and control subjects and then we compared the differences in pairwise stimuli among alcoholic and control subjects.

3.2.1. *Comparison of stimulus differences between alcoholic and control subjects*

For comparison of regionwise energy values between alcoholic and control subjects, the same MANOVA analyses as complexity analysis between two groups of subjects were carried out.

Table 5 shows the regional energy comparison between alcoholic and control subjects. The results indicate significant differences between energy of alcoholic and control subjects for all of the regions regardless of the type of picture stimulus. As a result of this analysis, we could easily conclude that the alcoholic subjects

Table 5. Energy comparison between alcoholic and control subjects.

	S1 Picture Stimulus		S2M Picture Stimulus		S2N Picture Stimulus	
Region	Hypothesis	p-value	Hypothesis	p-value	Hypothesis	p-value
Frontal	1	0.04	1	0.01	1	0.02
Temporal	1	0.00	1	0.00	1	0.00
Central	1	0.00	1	0.03	1	0.01
Occipital	1	0.00	1	0.00	1	0.00
Parietal	1	0.00	1	0.00	1	0.00

exhibited a decreased energy level as compared to control subjects for all regions of the brain. These decreased energy levels in alcoholic subjects could be due to the impairments in the information processing capacity of the brain caused by long-term alcohol abuse.

3.2.2. *Pairwise stimuli difference among alcoholic and control subjects*

Similar to the pairwise stimuli comparison among two groups of subjects using complexity values, we performed several MANOVA tests to compare regionwise energy values evoked by different stimulus conditions, i.e. S1 and S2M, S1 and S2N, S2M and S2N.

Table 6 shows the results of pairwise stimuli comparison among alcoholic and control subjects. Control subjects indicated differences for frontal, central, and temporal regions while alcoholics indicated differences for all parts of the brain for S1 and S2M stimuli comparison. It is known that mental processing of a visual stimulus results in fast sensory reception occurring in visual cortex (occipital lobe) followed by slower cognitive activity in frontal and parietal lobes (short-term memory recall and cognitive processing of stimulus).[5] Assuming that there are no impairments in information processing for control subjects, the possible reason for differences in energy of S1 and S2M for alcoholic subjects in occipital and parietal regions could

Table 6. Energy comparison of picture stimulus among alcoholic and control subjects.

	Alcoholic Subjects		Control Subjects	
	S1&S2M Picture Stimulus		S1&S2M Picture Stimulus	
Region	Hypothesis	p-value	Hypothesis	p-value
Frontal	1	0.00	1	0.00
Temporal	1	0.00	1	0.00
Central	1	0.00	1	0.00
Occipital	1	0.00	0	0.27
Parietal	1	0.00	0	0.09
	S1&S2N Picture Stimulus		S1&S2N Picture Stimulus	
Region	Hypothesis	p-value	Hypothesis	p-value
Frontal	1	0.00	1	0.00
Temporal	1	0.00	1	0.00
Central	1	0.00	1	0.00
Occipital	1	0.00	0	0.20
Parietal	1	0.00	1	0.01
	S2M&S2N Picture Stimulus		S2M&S2N Picture Stimulus	
Region	Hypothesis	p-value	Hypothesis	p-value
Frontal	0	0.52	0	0.90
Temporal	0	0.65	0	0.24
Central	0	0.26	0	0.95
Occipital	0	0.41	0	0.76
Parietal	0	0.93	0	0.72

be that when the alcoholic subjects were exposed to the second picture, the energy of these regions increase due to impairments in cognitive processing at these regions while they are trying to compare S2M to S1.

In a similar fashion, alcoholic subjects indicated differences for all regions while controls indicated differences in all regions except for occipital (visual cortex) for S1 and S2N stimuli comparison. Here when the subjects are exposed to first and second nonmatching stimulus only occipital region is invoked as they respond both of the stimulus as a new incoming visual stimulus. Similar to the previous case the alcoholics had increased energy in the occipital region when they were exposed to second nonmatching stimulus possibly due to deficits in mental processing activity at alcoholic subjects.

When S2M and S2N were compared, the results indicated no differences in any region.

4. Discussion

Conventionally the validity of applying nonlinear dynamic methods to EEG should be investigated using surrogate data method as suggested by Kaplan *et al.*[16] Surrogate time series are artificially generated time series that retain the linear properties of original signal.[16,18] Basically this method is used to confirm the presence of nonlinear dynamics in the biological signals (for example EEG and ECG[16,17]). For testing the nonlinearity, a discriminating statistic should be selected to extract the test statistics of original and surrogate data and perform rank based t-test to accept or reject the null hypothesis of linearity. There are lots of test statistics that can be used to test linearity such as delay vector variance method,[17] correlation dimension,[16] and nonlinear prediction error.[16] Detecting nonlinearity or linearity of signals allows us to know if the utilized analysis techniques are appropriate. In the present study, the presence of nonlinear structure in the EEG signals was not investigated before actual nonlinear complexity analysis which could be considered as a limitation of our study.

In this study, we have investigated the complexity and the energy of VEP signals to analyze the electrophysiological differences between alcoholic and control subjects. We have shown that there are significant differences in complexity between alcoholic and control subjects in almost all regions of the brain in which the complexity of alcoholic subjects are higher compared to control subjects. This can be due to the effects of long-term alcohol abuse. When we considered the differences between pairs of picture stimuli among alcoholic and control subjects, the results indicated that frontal, temporal, and central regions becomes more complex during S2M as compared to S1 whereas the results also indicated that the central region becomes more complex during S2N as compared to S1. These were true for both alcoholic and control subjects.

The energy analysis indicated that there are significant differences between alcoholics and controls in which the VEP signals of control subjects exhibit more energy

compared to alcoholic subjects. Again, this could be due to the impairments in cognitive processing capacity of alcoholic subjects. Considering the pairwise stimuli differences among alcoholic subjects, the results indicated that the VEP signals exhibit more energy during S2M and S2N as compared to S1 in all regions. When the control subjects were considered, higher energy was indicated only in frontal, temporal, and central regions in the case of S2M compared to S1 and in frontal, temporal, central, and parietal regions in the case of S2N compared to S1.

As a conclusion; for both energy and complexity analysis between alcoholic and control subjects, the results of this study showed that there are differences mostly in occipital, parietal, and frontal lobes. These parts of the brain are known to evoke when perception and cognitive processing of a visual stimulus occurs.[8] These differences in complexity and energy between alcoholic and control subjects indicate that there are impairments in cognitive processing of alcoholic subjects due to long-term alcohol abuse.

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