Recurrence plot analysis of functional brain connectivity during bistable visual perception

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***Abstract*—To develop fully-featured brain-computer interfaces it is crucial to study the behaviour of the brain in ambiguous situations. In this study, we analyzed the EEG data recorded during the perception of the bistable image - Necker's cube with the varying intensity of the lines. The image was demonstrated to the test person for one second and the person was asked to decide whether the cube is right-oriented or left-oriented and to push the corresponding data. During these actions the brain activity was recorded using 31-channel EEG, electrodes were placed according to the 10-20 system. The analysis, which was performed with the application of joint recurrence plots, suggests the existence of the synchronization between the channels of the frontal and occipital lobes. We believe that more rigorous research could reveal statistically significant brain connections and their dependence on physiological factors. Besides, this study may be significant for the development of the self-learning adaptive control systems.**

Keywords—brain, ambiguous images, EEG, recurrence analysis

I. INTRODUCTION

The brain is by far the most complicated organ for study and yet it is one of the most important human parts that are required to be studied. Understanding what lies under the important processes happening in our brain is the key to understanding the mechanisms of particular neurological disorders. This understanding is crucial for designing the rehabilitation methods, brain-computer interfaces for helping people and, moreover, develop artificial intelligence systems with human-like reasoning.

One of the aspects that require this study is perceiving the ambiguous situations and reacting to them. We believe that the study of the perception of bistable images may bring us closer to this understanding.

We analyze the brain activity EEG recorded during the perception of the Necker's cube. Previous studies revealed the existence of two different scenarios based on the alpha- and beta- waves activity [1-2]. In this study, we are trying to find the correlation between the scenarios of brain activity and the perceived orientation of the cube. For performing the analysis we used the joint recurrence plot analysis [3-4].

I. DATA DESCRIPTION

The data was collected on three persons. It contains experimental EEG signals recorded during the perception of bistable images (the Necker's cube). The data is stored with the marks of the decision on the orientation of the cube. Signals were recorded for three seconds: one second before the demonstration of the image and two seconds after. In my analysis, I extracted one-second interval and two-second interval right after the image demonstration and choose 40 random experiments for each person.

II. METHODS

The main used method of analysis is a recurrence plot analysis. Firstly, the analysis was performed for data recorded on each person separately.

1) Extracting one-second interval and two-second interval data after the cube demonstration and performing the same action sequence for both cases.

2) Picking 40 random experiment samples.

3) Creating joint recurrence plots for each possible channel pairs. Joint recurrence plot in this case is the matrix, which is defined for channels $ch1$ and $ch2$ as $R_{i,j} = \Theta(\xi_{ch1} - |ch1_i - ch1_j|) * \Theta(\xi_{ch2} - |ch2_i - ch2_j|)$. The maximum possible recurrence rate for each of the plots was chosen to be 0.4.

4) For each channel pair calculating the sum of the recurrence rates throughout 40 experiments. The recurrence rate is defined as $RR = \frac{1}{N^2}\sum_{i,j=1}^{N} R_{i,j}$, where R is the recurrence matrix and for this case $N = 250$ for one-second interval and $N = 500$ for two-second interval.

5) Calculating the mean value and mean squared error for the recurrence rate of the channel pairs.

6) Visualizing brain networks. For the picture to be not to complicated the visualization is for the most significant connections (for ones with at least 60% of the maximum recurrence rate), where the weights of the edges are the mean recurrence rate values.

Secondly, previously analyzed data was aggregated and visualized in quite the same way as the data for each person: recurrence rates were summed up and the brain network was built for the most significant connections.

III. RESULTS

On the cubes that were recognized as left-oriented: No apparent connections were detected.

On the cubes that were recognized as right-oriented: The connection was detected between several channels, which are capturing frontal lobe and prefrontal cortex activity. The

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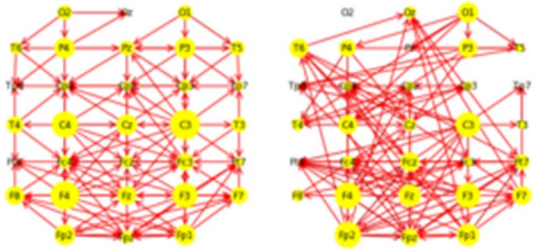
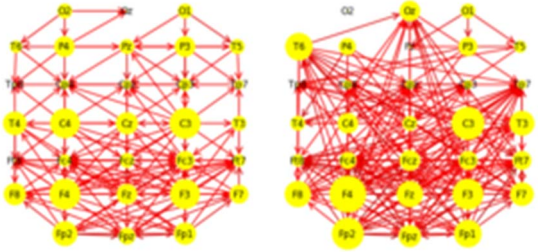
synchronization was revealed between channels F3 and Ft8, channels Fp2 and Fcz and channels Fp1 and Ft7 (the recurrence rate is ≈0.315 when the maximum possible recurrence rate is 0.4).



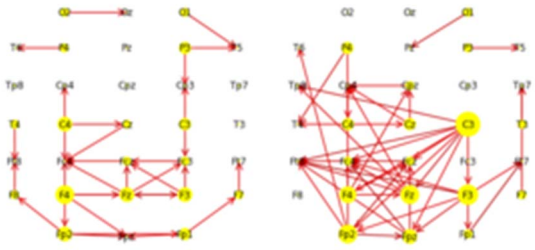
(a)Left-oriented cubes (b)Right-oriented cubes

Fig. 1. Brain connectivity map for the one-second interval combined for all three persons.
a) The strongest connections are located mainly on the frontal and central lobes (channels Fz-Fcz, F4-Fc4, F3-Fz, Fp2-Fpz, all with the recurrence rate ≈0.27 when the maximum possible recurrence rate is 0.4).
b) The strongest connections are found on the frontal and central lobes (channels F3-Ft8, Fp2-Fcz, Fp1-Ft7 with the recurrence rate ≈0.29 when the maximum possible recurrence rate is 0.4) and on the temporal lobe (channel T6 connected with the channels on the frontal lobe).



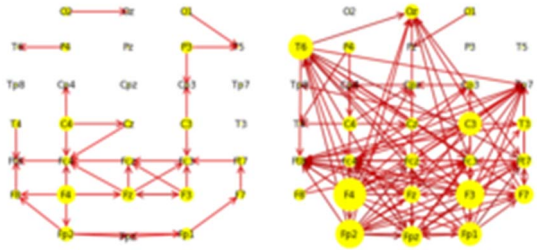
(a)Left-oriented cubes (b)Right-oriented cubes

Fig. 2. Brain connectivity map for the two-second interval combined for all three persons.
a) The strongest connections are found on the frontal and central lobes (channels Fp2-Fpz, F3-Fz, F3-Fc3, F4-Fcz, Fz-Fcz with the recurrence rate ≈0.275 when the maximum possible recurrence rate is 0.4).
b) The strongest connections are found on the frontal lobe (channels Fp2-Fcz, F3-Ft8, Fp1-Ft7 with the mean recurrence rate ≈0.31 when the maximum possible recurrence rate is 0.4), on the central lobe (C3 connected with the channels of the frontal lobe), on the temporal lobe (T6 connected with the channels of the frontal lobe) and on the occipital lobe (Oz connected with the channels of the frontal lobe).



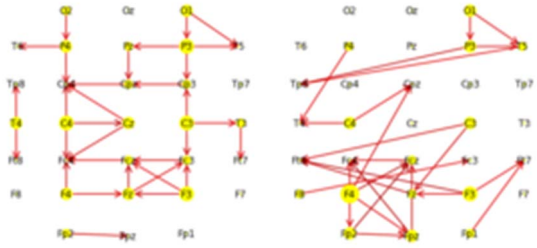
(a)Left-oriented cubes (b)Right-oriented cubes

Fig. 3. Brain connectivity map for the one-second interval for the first person.
a) The strongest connections are found on the frontal lobe. (channels F3-Fz, Fp2-Fpz, F4-Fc4 with the recurrence rate ≈ 0.3 when the maximum possible recurrence rate is 0.4).
b) The strongest connections are found in the right hemisphere: frontal and central lobes (channels F3-Ft8, Fp1-Ft7, Fp2-Fpz, Fpz-Fc4, C3-Ft8 with the recurrence rate ≈ 0.31 when the maximum possible recurrence rate is 0.4).



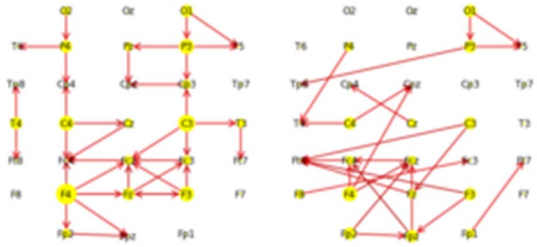
(a)Left-oriented cubes (b)Right-oriented cubes

Fig. 4. Brain connectivity map for the two-second interval for the first person.
a) The strongest connections are found on the frontal and central lobes (channels F3-Fz, Fp2-Fpz, F3-Fc3, F4-Fc4, C3-Fc3 with the recurrence rate ≈ 0.29 when the maximum possible recurrence rate is 0.4).
b) The strongest connections are found on the frontal lobe(channels Fp1-Ft7, Fp2-Fpz, Fp2-Fcz, F3-Ft8 with the recurrence rate ≈ 0.36 when the maximum possible recurrence rate is 0.4), temporal lobe (T6 connected with the channels of the frontal lobe) and occipital lobe (Oz connected with the channels of the frontal lobe).



(a)Left-oriented cubes (b)Right-oriented cubes

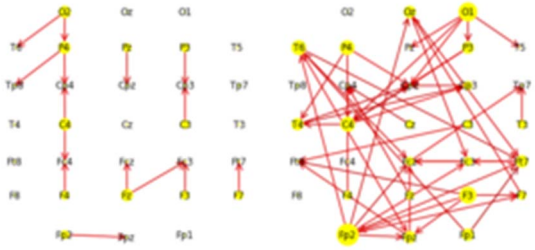
Fig. 5. Brain connectivity map for the one-second interval for the second person.
a) There is no certain area where the strongest connections are found (the most significant are channels Fz-Fcz, C4-Cz, F4-Fc4, C3-Fc3, Pz-Cpz with the recurrence rate ≈ 0.28 when the maximum possible recurrence rate is 0.4).
b) The strongest connections are found on the frontal and parietal lobes, the most connections are located on the right hemisphere (channels Fp2-Fcz, Fpz-Fc4, F4-Fcz, F3-Ft8, P3-Tp8 with the recurrence rate ≈ 0.31 when the maximum possible recurrence rate is 0.4).



(a)Left-oriented cubes (b)Right-oriented cubes

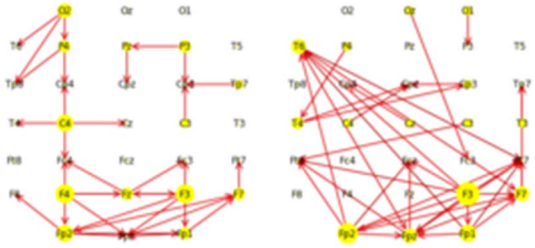
Fig. 6. Brain connectivity map for the two-second interval for the second person.
a) The strongest connections are found on the frontal, central and parietal lobes, all, except channels Fz-Fcz, are not on the midline (channels F4-Fc4, C3-Fc3, C4-Fc4, F3-Fc3 with the recurrence rate 0.29 when the maximum possible recurrence rate is 0.4).
b) The strongest connections on the left hemisphere are found on the

occipital, parietal and temporal lobes (channels C3-Ft8, P3-Tp8, C3-Fz with the recurrence rate ≈ 0.29 when the maximum possible recurrence rate is 0.4), on the right hemisphere - on the frontal and central lobes (channels Fc4-Fz, Fp2-Fcz, F4-Fcz with the recurrence rate ≈ 0.3 when the maximum possible recurrence rate is 0.4).



(a)Left-oriented cubes (b)Right-oriented cubes

Fig. 7. Brain connectivity map for the one-second interval for the third person.
a) There is no certain area where the strongest connections are found (the most significant are channels Pz-Cpz, P3-Cp3, F3-Fc3, O2-T6 with the recurrence rate ≈ 0.27 when the maximum possible recurrence rate is 0.4).
b) The strongest connections are found on the frontal, central and occipital lobes (channels Fp1-Ft7, C4-Cpz, Cz-Cp4, Fp2-Fcz, F3-Ft8 with the recurrence rate ≈ 0.3 when the maximum possible recurrence rate is 0.4).



(a)Left-oriented cubes (b)Right-oriented cubes

Fig. 8. Brain connectivity map for the two-second interval for the third person.
a) The strongest connections on the right hemisphere are found on the occipital, parietal and temporal lobes (channels Pz-Cpz, F8-T6, O2-T6 with the recurrence rate ≈ 0.27 when the maximum possible recurrence rate is 0.4), on the left hemisphere - on the frontal lobe (channels F3-Fc3, F7-Ft7, Fp1-Fpz with the recurrence rate ≈ 0.27 when the maximum possible recurrence rate is 0.4).
b) The strongest connections are found on the frontal lobe (channels Fp1-Ft7, Fp2-Fcz, F3-Ft8, F3-Fpz with the recurrence rate ≈ 0.3 when the maximum possible recurrence rate is 0.4) and on the temporal (T6-Fp1, T6-Ft7 with the recurrence rate ≈ 0.32 when the maximum possible recurrence rate is 0.4).

IV. Conclusion

We analyzed the EEG data recorded during the perception of bistable images (the Necker's cube). The synchronization of the activity on the occipital and the frontal lobes was revealed. This can be explained by the receiving visual information by the occipital lobe (the cube image) and transferring it to the frontal lobe as it is responsible for the conscious decisions (in our case, whether the cube is left-oriented or right-oriented).

Just as important, we found that EEG channels with the strongest connections are the same when perceiving the cube as the right-oriented. Contrariwise, when perceiving the cube as the right-oriented, the channels with the strongest connections may vary from person to person.

However, current discoveries require an in-depth study. The next steps are: analyzing data on more people and applying the nonparametric statistical test (the permutation test) to reduce the false alarm rate. Furthermore, research should be done to reveal whether there is a correlation between the dominant eye and brain activity when perceiving bistable images.

We firmly believe that the significance of our results is not limited to the visual perception of the Necker's cube images. The studied data may be crucial when designing the self-learning adaptive control systems, particularly, when designing the behavior when coming across mixed pictures.

Acknowledgment

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