A DMC_x^2 Multi-channel cross-correlation analyses of a motor/imaginary human activity experiment electroencephalogram (EEG) recordings

Fernando Ferraz Ribeiro[1,4◑], Andrea de Almeida Brito[3◑], Florêncio Mendes Oliveira Filho[5¤], Juan Alberto Leyva Cruz[2], Gilney Figueira Zebende[2]

1 Federal University of Bahia, Brazil
2 State University of Feira de Santana, Bahia, Brazil
3 Department of Mathematic, Federal Institute of Education, Science and Techinology , Salvador, Bahia, Brazil
4 PPGM, State University of Feira de Santana, Bahia, Brazil
5 Computation Engeneering, SENAI CIMATEC University Center, Salvador, Bahia, Brazil

◑These authors contributed equally to this work.
‡These authors also contributed equally to this work.
¤Current Address: Dept/Program/Center, Institution Name, City, State, Country
†Deceased
¶Membership list can be found in the Acknowledgments section.
* correspondingauthor@institute.edu

Abstract

This paper presents an investigation on the electroencephalogram (EEG) 64-channels recordings of a motor/imaginary experiment, using the detrended multiple cross-correlation coefficient (DMC_x^2). Analyzing data from 4 channels, $F_3$32, $F_6$37 (frontal region of the head) and $P_3$49, $P_6$54 (parietal region of the head), the DMC_x^2 was applied to evaluate the correlation among one of the channels with the three others alternately. Analyzing all the motor/imaginary experiments and 108 of the 109 subjects, this research points to a pattern, detected on most of the subjects: Using channel $F_3$32 against the others, the correlation coefficient is higher compared to the other combinations. The reason why some persons don't match that pattern is still an open question.

Introduction

The electroencephalogram (EEG) is, in short, a technic that reads electrical signals from the brain activity with the use of sensors placed in the scalp of the patient and makes sense of this data. Impulses are amplified and recorded over time in parallel, generating one time serie for each sensor. The EEG equipment mesures the electric potential difference from each sensor position in relation with a reference sensor, usually placed in the ear lobe. Although the EEG is almost a centenary technic, in recent decades EEG has addressed new problems as brain-triggered neurorehabilitation treatments, experimental psychology or even computational neuroscience, due to it's versatility and accessibility combined with the advances in signal processing [1].

The recordings used are available at the Physionet on-line databank (`https://physionet.org/pn4/eegmmidb/`). The data is originated from a study that perform 14 experiments on a population of 109 subjects, Using 64 electrodes to record the brain signals. The first 2 experiments are baseline references, the subjects where resting with eyes opened end the second with eyes closed (one minute for each). The other four experiments are a combination of two categories with two possible options each $2 \times 2 \ = 4$. In general, the experiments consist of making the subjects react over visual stimulus: a target that appears on a screen. One category is about the target position, one option is a target that will aperar on the left or the right of the screen, in the other,the target will appear on the top or on the bottom of the screen. The second category determines if the subject will actually execute a body action related to the target position (Real) or if the corresponding action will be just imagined (Imaginary) by the subject. The tasks, with duration of two minutes, are described below:

- **Task 1: a target appears on either the left or the right side of the screen. The subject opens and closes the corresponding fist until the target disappears. Then the subject relaxes. (Real (L/R));**
- **Task 2: a target appears on either the left or the right side of the screen. The subject imagines opening and closing the corresponding fist until the target disappears. Then the subject relaxes. (Imag (L/R));**
- **Task 3: a target appears on either the top or the bottom of the screen. The subject opens and closes either both fists (if the target is on top) or both feet (if the target is on the bottom) until the target disappears. Then the subject relaxes. (Real (T/D));**
- **Task 4: a target appears on either the top or the bottom of the screen. The subject imagines opening and closing either both fists (if the target is on top) or both feet (if the target is on the bottom) until the target disappears. Then the subject relaxes. (Imag (T/D)).**

Table 1 presents witch Task is carried in each experiment number. Every subject executes the four tasks three times. Experiments 3, 7 and 11 applies Task 1 to the subjects, experiments 4, 8 and 12, Task 2, experiments 5, 9 and 13, Task 3 and experiments 6, 10 e 14 uses Task 4.

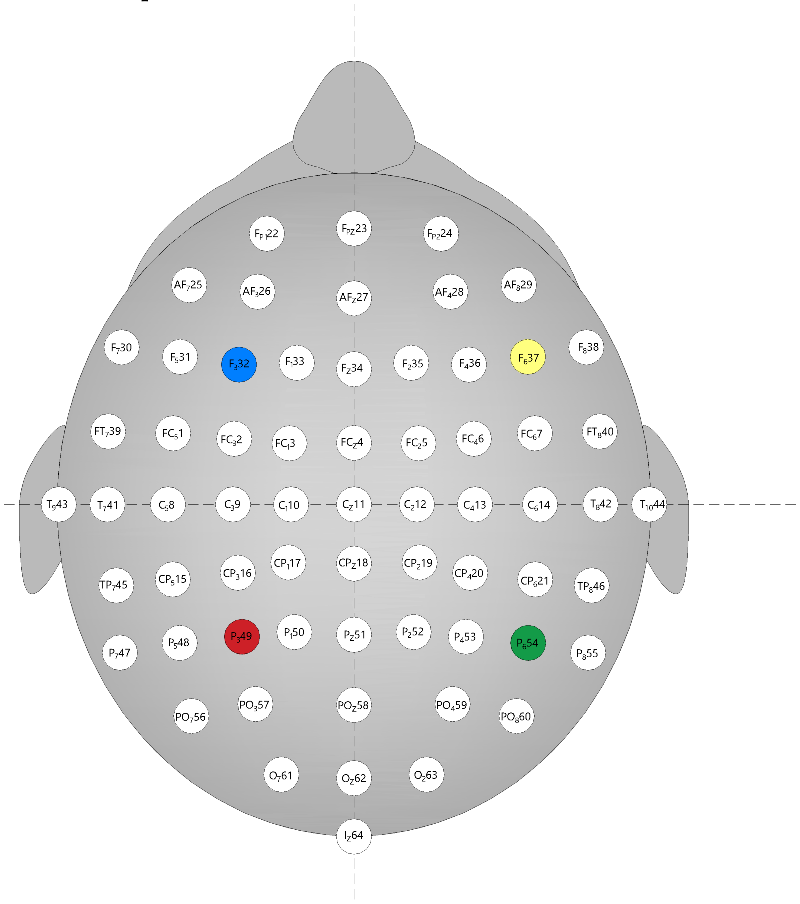
Table 1. Experiment x task relation

Experiment nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Baseline 1	x													
Baseline 2		x												
Task 1			x				x				x			
Task 2				x				x				x		
Task 3					x				x				x	
Task 4						x				x				x

The experiment and the executed tasks: Two one-minute baseline (eyes open/closed) and three two-minute of four Tasks.

The electrodes in all tasks and experiments where located as shown in Figure 1. The colored circles in Figure 1 correspond to the positions of the electrodes channels whose recordings were used in our analyses: $F_3$32 (blue) and $F_6$37 (yellow), on the frontal region of the head, and $P_3$49 (red) and $P_6$54 (green), on the parietal region of the head.

Fig 1. Electrodes position illustration.



Position of the 64 electrodes according to the international10-20 system (excluding electrodes Nz, F9, F10, FT9, FT10, A1, A2, TP9, TP10, P9, and P10). The colored dots: $F_3$32 (blue), $F_6$37 (yellow), $P_3$49 (red), $P_6$54 (green) identify the channels used in this research.

The four channels are alternately picked as dependent variable and the correlation against the other three are calculated by the application of the Detrended Multiple Cross-Correlation Coefficient (DMC_x^2) [2]

In the next sections we will present the dataset; the methodology used to analyze the data, including pre-processing strategies and criteria, and the DMC_x^2 method; the results, statistics and data visualization for the analyzed populations and individual results for randomly selected subjects. The discussion of the results and the conclusions are presented in sequence. In the supporting materials, a link to access all the calculations and data visualization for all the experiment subjects is available.

Materials and methods

The Physionet on-line databank is publicly available at `https://physionet.org/pn4/eegmmidb/`, presents recordings of the EEG experiments described in previous section. The data is provided in EDF (European data format) files. The files of all the experiments for every subject where downloaded using a web scraping script created by the authors using Python and the package Beautiful Soap.

The EDF files where opened using Python package *pyedflib* and translated into text files . In EEG experiments, usually the end of the recordings is filled with a sequence of zeroes, corresponding to the time gap between the shooting down of the EEG machine and the recording system. In this pre-processing stage, all the tailing zeroes sequences are eliminated from the records. To properly apply the DMC_x^2 calculations and the intended comparisons between experiments end subjects, all the time series must have the same length. The research find out the the experiment number 5 (Top/Down, Real) conducted with subject S106 has only 5808 valid recorded points. The second smallest time series has 15742 valid records (subject: S100, experiment: 12 -Left/Right, Imaginary).

The interval between each recorded value in this equipment is 6.25 ms, and the recordings on experiment 5 of subject S106 is 36.3 s. The duration is way smaller then the expected 2 minutes and the series is relatively small to the application os the DMC_x^2 method. Cutting all the subjects data to this duration implies in a great loss of data. The second smaller series of 15742 represents a total duration of 98.3875 s. The value was considered adequate to the DMC_x^2 method and the duration is about 82% of the expected duration. The decision was to eliminate subject S106 from the experiment and to cut all time series at recording point 15742. resulting in a total number of 108 subjects with all 12 experiments per subject lasting 98.3875 s.

The DMC_x^2 is part of a group of new statistical methods applied to long-range time series. The DFA method [3, 4] was proposed to identify self-affinity in of a signal. For long-memory series, the value of the $F_{DFA}(n)$ usually grow with the time scale n denoting a power-law, described by the auto-correlation exponent α. This method was already used to evaluate the self-affinity of the same channels of this same dataset analyzed in this study, concluding xthat the amplitude of fluctuation tends to be larger in the frontal channels "($F_3$32 and $F_6$37), if we compare with the channels located in the parietal region of the brain ($P_3$49 and $P_6$54)" [5]. Other works also applied DFA to evaluate different aspects of EEG signals [6] [7] [8].

The Detrended Cross-Correlation Coefficient,$DCCA$ [9], expand the idea of the DFA to analyze the long-range cross-correlation for two non-stationary time series, but the quantification of the level of this correlation is calculated by the ρ_{DCCA} , proposed tree year later [10] and statistically tested in the same year [11]. Equation 1 shows that the ρ_{DCCA} of two time series, x_a and x_b is calculated using the DFA and the $DCCA$ methods.

$$\rho_{x_a,x_b}(n) = \frac{F^2_{DCCA_{(xa,xb)}}(n)}{F_{DFA_{xa}}(n)F_{DFA_{xb}}(n)} \tag{1}$$

To analise the dataset, this study uses the Detrended Multiple Cross-Correlation Coefficient (DMC_x^2) [2]. This coefficient, is a generalization of the ρ_{DCCA} , and calculates the correlation of one time serie Y, defined dependent variable in relation of a number k of time series $[x_1, x_2 \ldots x_k]$, taken as independent variables. In equation 2, $\rho_{y,x_i}(n)$ is a vector containing the ρ_{DCCA} of Y against each one of the dependent variables, and matrix $\rho^{-1}(n)$ is the inverse matrix of the dependent variables in relation with each other, fora certain time scale.

$$DMC_x^2 \equiv \rho_{y,x_i}(n)^T \times \rho^{-1}(n) \times \rho_{y,x_i}(n) \tag{2}$$

Matrix $\rho(n)$ is presented in Equation 3. The main diagonal is filled with ones (1) because the ρ_{DCCA} correlation among a time serie and itself is always one. The ρ_{DCCA} correlation is independent of the order of the two time series in the equation (commutative property). Since ρ_{x_a,x_b} is equal to ρ_{x_b,x_a}, it's important to point that matrix $\rho(n)$ is symmetric with respect to the main diagonal.

$$\rho^{-1}(n) = \begin{pmatrix} 1 & \rho_{x_1,x_2}(n) & \rho_{x_1,x_3}(n) & \dots & \rho_{x_1,x_i}(n) \\ \rho_{x_2,x_1}(n) & 1 & \rho_{x_2,x_3}(n) & \dots & \rho_{x_2,x_i}(n) \\ \vdots & \vdots & \vdots & \dots & \vdots \\ \rho_{x_i,x_1}(n) & \rho_{x_i,x_2}(n) & \rho_{x_i,x_3}(n) & \dots & 1 \end{pmatrix}^{-1} \tag{3}$$

The calculation of the inverse matrix is the most time consuming step on the method. Replacing the equal values ($\rho_{x_a,x_b} = \rho_{x_b,x_a}$) the calculus of the DMC_x^2 with 3 independent variables $[x_1, x_2, x_3]$ against one dependent Y is presented in Equation 4.

$$\begin{aligned} DMC_x^2 \quad = \quad & (\rho^2_{X_2,X_3} \times \rho^2_{Y,X_1} - \rho^2_{Y,X_1} + \rho^2_{X_1,X_3} \times \rho^2_{Y,X_2} - \rho^2_{Y,X_2} + \\ & 2 \times \rho_{X_1,X_2} \times \rho_{Y,X_1} \times \rho_{Y,X_2} - 2 \times \rho_{X_1,X_3} \times \rho_{X_2,X_3} \times \rho_{Y,X_1} + \\ & \rho^2_{X_1,X_2} \times \rho^2_{Y,X_3} - \rho^2_{Y,X_3} + 2 \times \rho_{X_1,X_3} \times \rho_{Y,X_1} \times \rho_{Y,X_3} - \\ & 2 \times \rho_{X_1,X_2} \times \rho_{X_2,X_3} \times \rho_{Y,X_1} \times \rho_{Y,X_3} - \\ & 2 \times \rho_{X_1,X_2} \times \rho_{X_1,X_3} \times \rho_{Y,X_2} \times \rho_{Y,X_3} + \\ & 2 \times \rho_{X_2,X_3} \times \rho_{Y,X_2} \times \rho_{Y,X_3}) \quad / \\ & (\rho^2_{X_1,X_2} + \rho^2_{X_1,X_3} + \rho^2_{X_2,X_3} - 2 \times \rho_{X_1,X_2} \times \rho_{X_1,X_3} \times \rho^{-1}_{X_2,X_3}) \end{aligned} \tag{4}$$

Results

Fig 2

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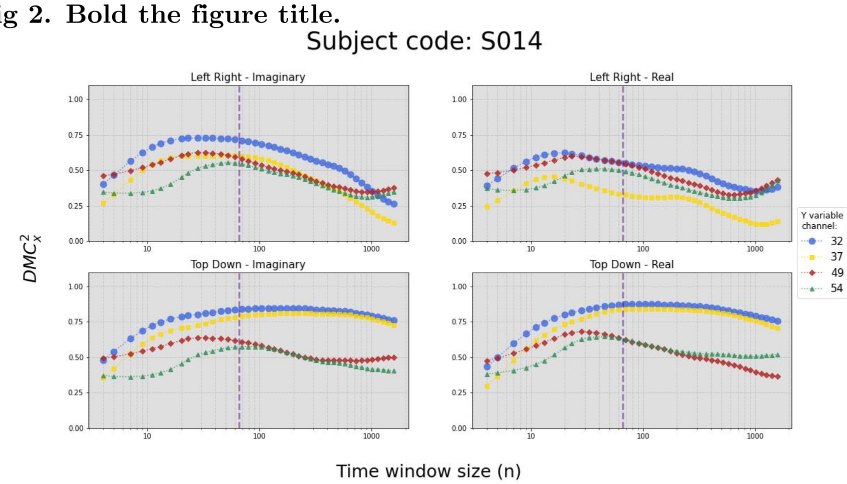

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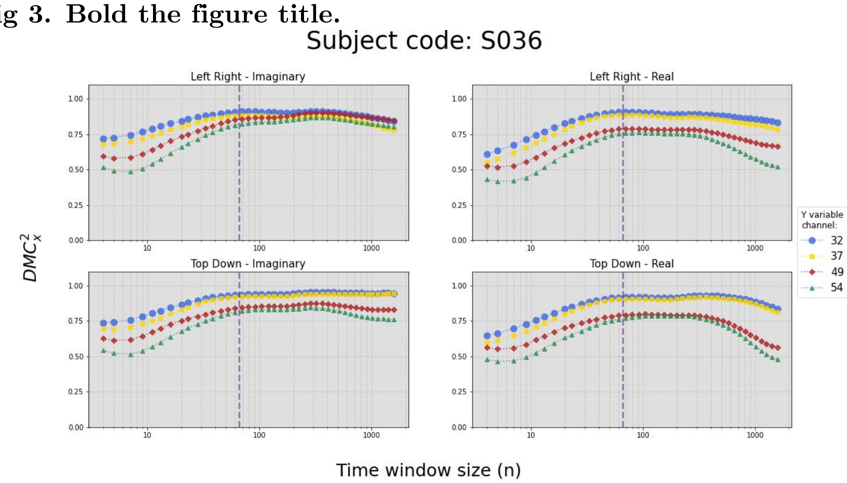

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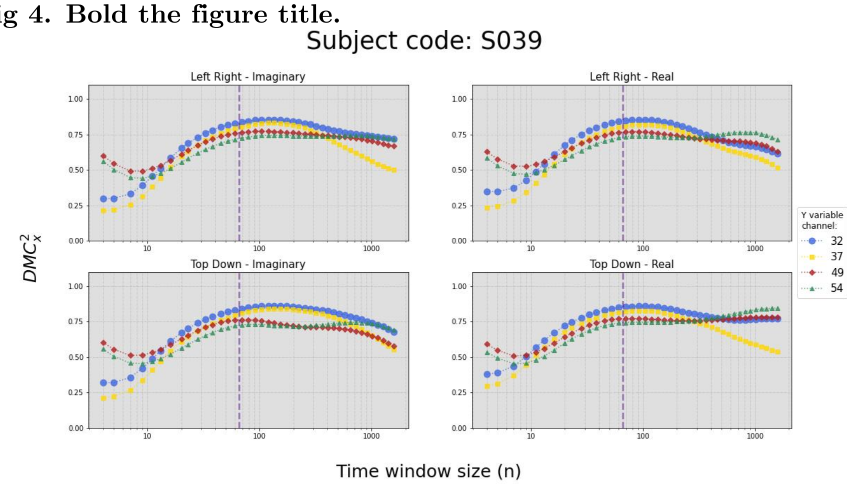

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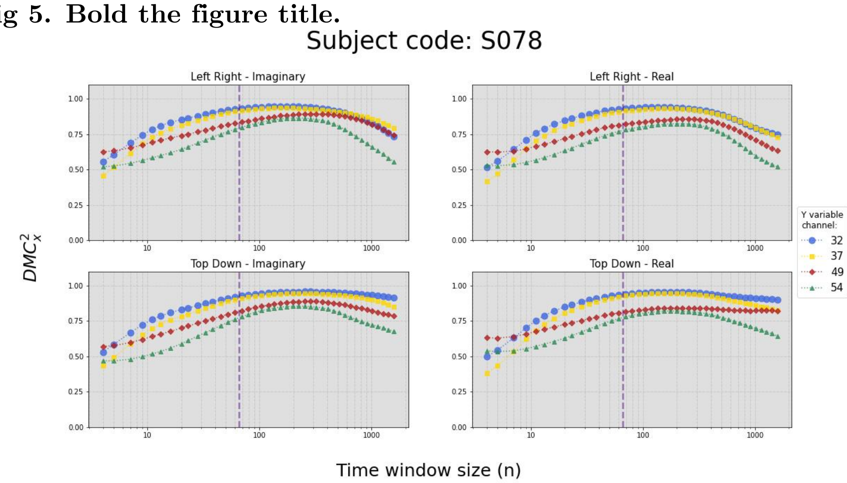

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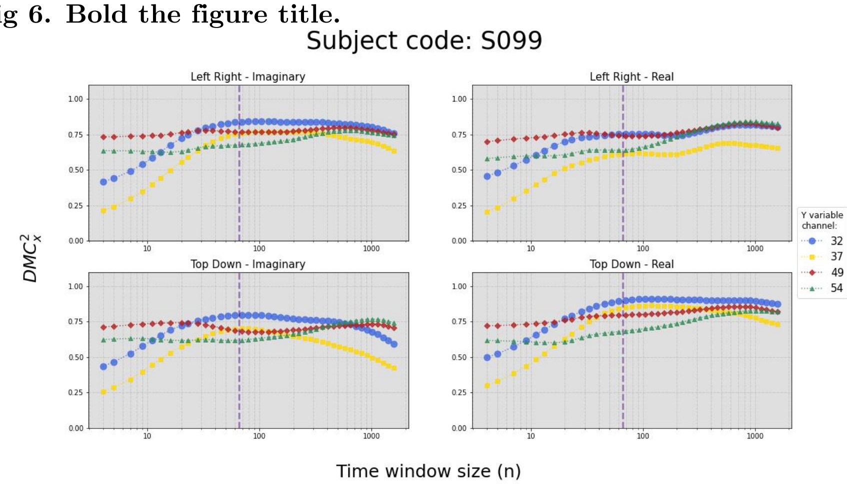

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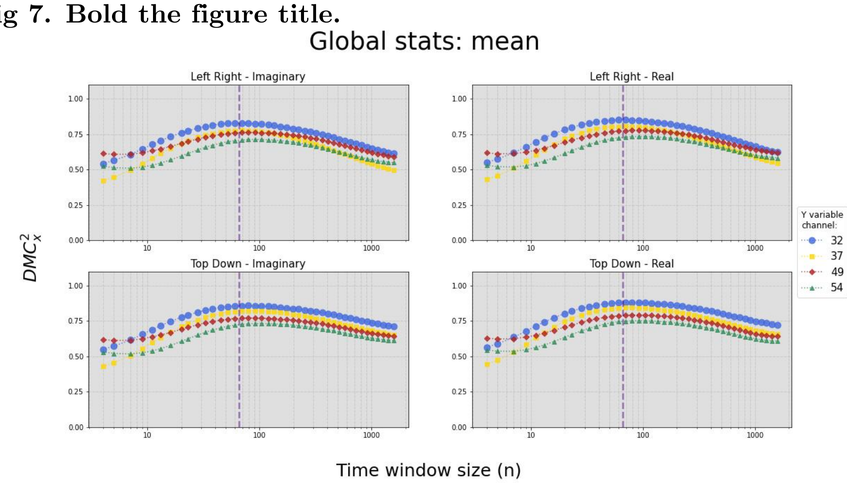

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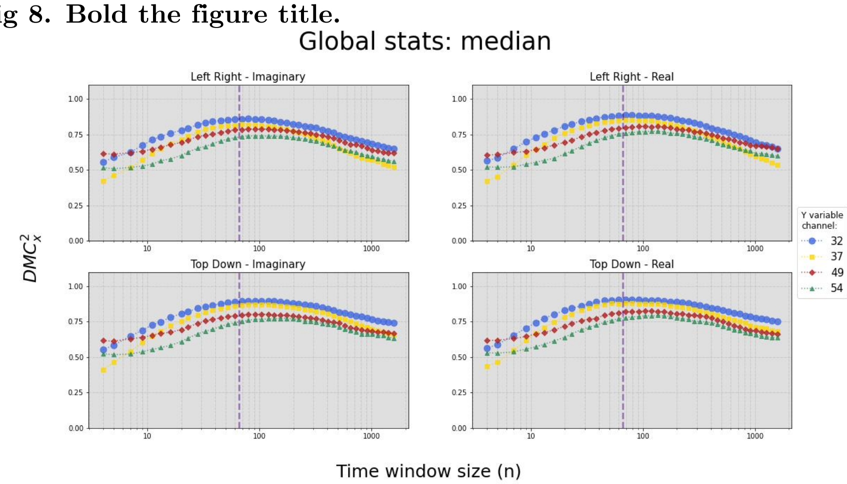

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Discussion

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Conclusion

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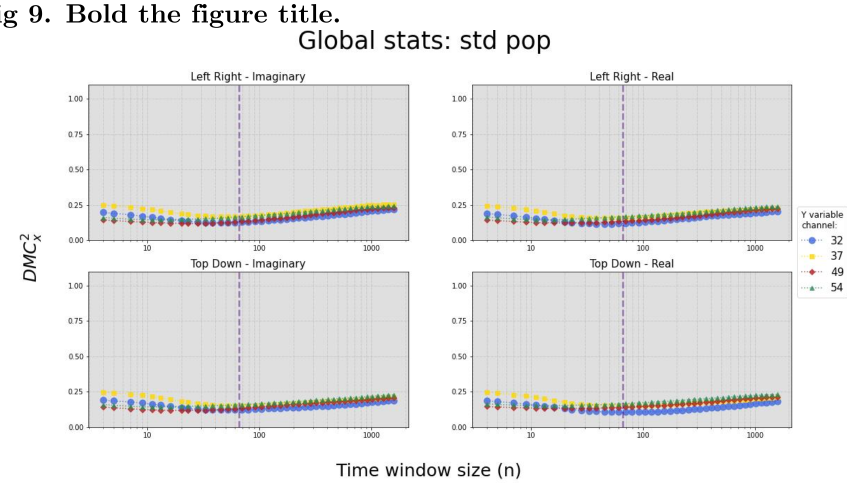

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Supporting information

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