# Synergistic and Redundant Brain-Heart Information in Patients with Focal Epilepsy*

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***Abstract*— In this work, partial information decomposition (PID) was applied to the time series of heart rate and EEG amplitude variability to investigate the dynamical interactions in brain-heart coupling before and after epileptic seizures. From ECG and EEG signals collected on 23 children suffering from focal epilepsy, the RR intervals and the EEG variance at ipsilateral and contralateral temporal electrodes were computed in four different time windows before and after the seizures. Static PID was used to obtain redundant, unique and synergistic components of the total information shared between the series of RR and EEG variance. Results highlight, in the progression from preictal to postictal states, a statistically significant change of mutual information at the ipsilateral electrode and of the synergy between brain locations.**

## I. Introduction

According to the "network physiology" approach, the human body can be considered as an integrated network, in which nodes correspond to organs continuously interacting with each other to produce different physio-pathological states [1]. A tool suitable to understand interactions and coupling between organs is information theory, which helps quantifying information shared and transferred between physiological systems [2]–[4]. In particular, Partial Information Decomposition (PID) allows to quantify the information exchange among multiple sources and a target system [2], [5]. In perspective, investigating the interactions among various body districts could help to shed light on the mechanisms underlying seizures attacks in epileptic patients. In a previous work [6] we studied pre- and post-ictal heart rate variability (HRV) features in epileptic children, combining time, frequency and information measures. In this work, we exploit the network physiology paradigm and PID to study dynamical brain-heart interactions between electroencephalographic (EEG) activity and HRV in children suffering from focal epilepsy studied well before, between and after seizures, with the aim to shed light on the physiological mechanisms leading to seizure onset in the pre-ictal phase and to the recovery of normal autonomic function in the post-ictal phase.

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## II. Materials and Methods

### A. Experimental protocol

Data analyzed in this study have been acquired at the TMO 'Psychiatry' clinic of Kyiv (Ukraine) on 23 pediatric patients (14 males, 9 females) suffering from focal epilepsy. In all the patients, electrocardiographic (ECG, 250 Hz sampling rate) and EEG signals (20 electrodes, 250 Hz sampling rate) were recorded synchronously. Further information on the typologies of focal epilepsy diagnosed on the patients and on data acquisition can be found in [6].

### B. Data analysis

HRV and brain activity were measured extracting R-R intervals from the ECG and computing the EEG variance (EEGv), respectively. Both time series were extracted on a beat-to-beat basis, with EEGv computed over 2-s windows aligned with the R peaks of the ECG. According to a non patient-specific approach, 143 synchronous time series of 300 points each were obtained in four different time windows (10 min and 10 s before and after the seizure). Such time series length was chosen to comply with common short-term HRV requirements [6]. R-R intervals were extracted employing a Pan-Tompkins method modified to deal with noisy ECG tracks and remove outliers [6]. EEG signals were filtered with band-pass zero-phase IIR Butterworth filter [0.5-42 Hz]. PID was carried out considering the total power on ipsilateral and contralateral temporal electrodes (left (T3) or right (T4) temporal according to the seizure), in all four time windows. Temporal electrodes were taken into account being the nearest to seizure location.

Denoting the RR series as $X$ and $Y=\{Y_1, Y_2\}$ the vector of ipsi- and contra-lateral EEGv series, we quantify brain-heart coupling using the mutual information (MI) [4]:

$$I(X;Y) = H(X) - H(X|Y) \tag{1}$$

where $H(\cdot)$ represents entropy, and $H(\cdot|\cdot)$ conditional entropy. The analysis was performed under the assumption of linearity and gaussianity, so that linear regression models could be employed to compute the conditional entropy [7]:

$$H(X|Y) = \frac{1}{2}\log\left(2\pi e\left|\Sigma_{X|Y}\right|\right) \tag{2}$$

being $\Sigma_{X|Y}$ the partial covariance. Further details can be found in [8]. Thanks to PID, the information shared between the processes can be decomposed into unique ($U$), redundant ($R$) and synergistic ($S$) contributions [2]:

$$I(X;Y_1,Y_2) = U(X;Y_1) + U(X;Y_2) + R(X;Y_1,Y_2) + S(X;Y_1,Y_2) \tag{3}$$

$$I(X;Y_1) = U(X;Y_1) + R(X;Y_1,Y_2) \tag{4}$$

$$I(X;Y_2) = U(X;Y_2) + R(X;Y_1,Y_2) \tag{5}$$

Redundancy can be defined as the minimum information shared separately between each source and the target [2], [9]:

$$R(X;Y_1,Y_2) = \min\{I(X;Y_1); I(X;Y_2)\} \quad . \qquad (6)$$

## III. Results and Discussion

Figure 1 shows the distributions across patients of MI between (a) RR and EEGv from both temporal electrodes T3 and T4; (b) RR and EEGv from the ipsilateral electrode, (c) RR and EEGv from the contralateral electrode in the four considered epochs. The non-parametric Kruskal-Wallis and post-hoc Wilcoxon tests with Bonferroni-Holm correction for multiple comparisons ($n$=3) were applied to test statistical differences among the distributions in consecutive time windows. In future works, non-consecutive time windows will be also analyzed. In Fig. 1, the hash symbols "#" indicate results of the Kruskal-Wallis test, red if $0.05 < p < 0.1$, black if $p < 0.05$, while reported $p$-values refer to post-hoc test. Black lines depict the trend of median values of the distributions.

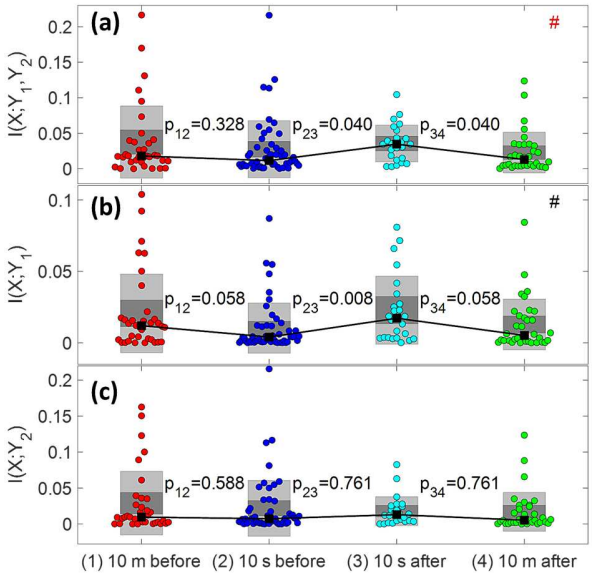


Figure 1. MI between: (a) the RR interval and EEG variance from both temporal electrodes T3 and T4; (b) RR and ipsilateral EEG variance; (c) RR and contralateral EEG variance, in the four considered time windows.

A statistically significant increase of MI between RR and EEGv from both temporal electrodes was detected just after the seizure, with recovery of values 10 minutes after the seizure (Fig. 1(a)). Such increase of brain-heart interactions is mainly accounted by the EEGv measured at the ipsilateral electrode (Fig. 1(b)), while no statistically significant differences were detected when analyzing the MI between RR and contralateral EEGv (Fig. 1(c)). The unique information transfer, not shown here for brevity, showed no significant trends across windows.

Figure 2 depicts the distributions of (a) redundant and (b) synergistic information that ipsilateral and contralateral EEGv share with RR. The redundant contribution appears to vary significantly only close to the seizure, while a marked increase of the synergistic contribution is instead detected going from 10 s before to 10 s after the seizure, with recovery to preictal values after 10 min. Increasing the synergistic contribution implies a stronger brain-heart coupling just after the seizure, since the two sources share a larger amount of information with the target when taken together than when considered separately [9].

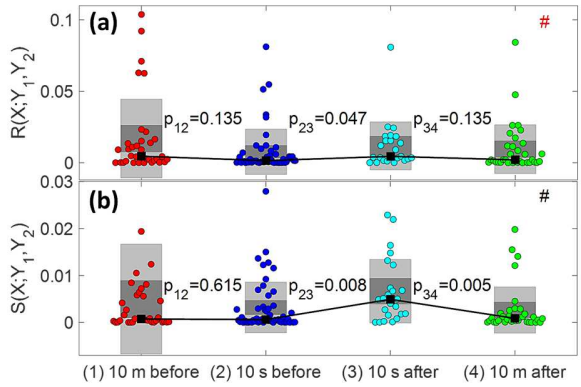


Figure 2. Results of PID: distributions of (a) redundant and (b) synergistic contributions in the four time windows.

## IV. Conclusion

Our results highlight that focal epilepsy is associated to a significant increase of the mutual information between brain and heart dynamics, manifested just after the seizure in comparison with the preictal period. While this increased coupling between brain and heart dynamics originates mainly from the ipsilateral brain hemisphere, PID reveals that a higher synergy between ipsilateral and contralateral EEG variance also contributes to the higher mutual information shared with heart rate variability. In perspective, these findings could be exploited to support investigations on the origin of epileptiform activity in the brain, and to highlight patterns of brain-heart coupling which can be promising for classification or characterization algorithms.

## References


[1] R. P. Bartsch, K. K. L. Liu, A. Bashan, and P. C. Ivanov, "Network Physiology: How Organ Systems Dynamically Interact," *PLoS One*, vol. 10, no. 11, p. e0142143, Nov. 2015.

[2] A. B. Barrett, "Exploration of synergistic and redundant information sharing in static and dynamical Gaussian systems," *Phys. Rev. E*, vol. 91, no. 5, p. 52802, May 2015.

[3] A. Silvani, G. Calandra-Buonaura, R. A. L. Dampney, and P. Cortelli, "Brain–heart interactions: physiology and clinical implications," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 374, no. 2067, p. 20150181, 2016.

[4] M. Zanetti *et al.*, "Information Dynamics of the Brain, Cardiovascular and Respiratory Network during Different Levels of Mental Stress," *Entropy* , vol. 21, no. 3. 2019.

[5] J. Lizier, N. Bertschinger, J. Jost, and M. Wibral, "Information decomposition of target effects from multi-source interactions: perspectives on previous, current and future work." Multidisciplinary Digital Publishing Institute, 2018.

[6] R. Pernice *et al.*, "Time, frequency and information domain analysis of short-term heart rate variability before and after focal and generalized seizures in epileptic children," *Physiol. Meas.*, vol. 40, no. 7, p. 74003, 2019.

[7] L. Faes, A. Porta, G. Nollo, and M. Javorka, "Information Decomposition in Multivariate Systems: Definitions, Implementation and Application to Cardiovascular Networks," *Entropy* , vol. 19, no. 1. 2017.

[8] R. Pernice, M. Zanetti, G. Nollo, M. De Cecco, A. Busacca, and L. Faes, "Mutual Information Analysis of Brain-Body Interactions during different Levels of Mental stress*," in *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2019, pp. 6176–6179.

[9] J. Krohova *et al.*, "Multiscale Information Decomposition Dissects Control Mechanisms of Heart Rate Variability at Rest and During Physiological Stress," *Entropy* , vol. 21, no. 5. 2019.