WHY TONONI IS WRONG; EPILEPTIC SEIZURE IS MORE COMPLEX EITHER THAN SLEEP OR THE RESTING STATE

Seán O Nualláin and Tom Doris

ABSTRACT: ECOG data obtained from a patient under conditions of resting brain, sleep and epileptic seizure were analyzed. Contrary to some theorists, the seizure state was found to be informationally the most complex of the three states.

KEYWORDS: Tononi; epileptic seizure; principle component analysis; dynamic time warping.

METHODOLOGY

Data were obtained from a patient undergoing brain surgery using 64 electrodes applied directly to the brain (Freeman et al, 2008). The data were analyzed using principal component analysis (PCA) followed by dynamic time warping (DTW).

RESULTS

Sleep signal is least complex/disordered under PCA, first component explains 97%, awake is next, with 93% explained by the first component, while seizure has just 63% explained by first component.

```
> summary(sleep.pca)
Importance of components:
                          Comp.1       Comp.2          Comp.3          Comp.4
Standard deviation     3617.52558 558.22276538 1.995012e+02 9.979809e+01
Proportion of Variance    0.97218    0.02314934 2.956748e-03 7.398913e-04
Cumulative Proportion     0.97218    0.99532935 9.982861e-01 9.990260e-01

> summary(awake.pca)
Importance of components:
                          Comp.1          Comp.2          Comp.3          Comp.4
Standard deviation     2367.1654748 604.46046432 1.478273e+02 1.040318e+02
Proportion of Variance    0.9312534    0.0607220 3.631781e-03 1.798633e-03
Cumulative Proportion     0.9312534    0.99197549 9.956073e-01 9.974059e-01

> summary(seizure.pca)
Importance of components:
                          Comp.1       Comp.2          Comp.3          Comp.4
Standard deviation     775.4846745 527.3334430 173.58648671 119.62947975
Proportion of Variance    0.6364108    0.2942807 0.03188768 0.01514494
Cumulative Proportion     0.6364108    0.9306914 0.96257912 0.97772406
```

We confirmed these results with dynamic time-warping (DTW);

```
> mean(seizure.dtw.mat)
[1] 6.731411
> mean(awake.dtw.mat)
[1] 5.580975
> mean(sleep.dtw.mat)
[1] 4.204780
```

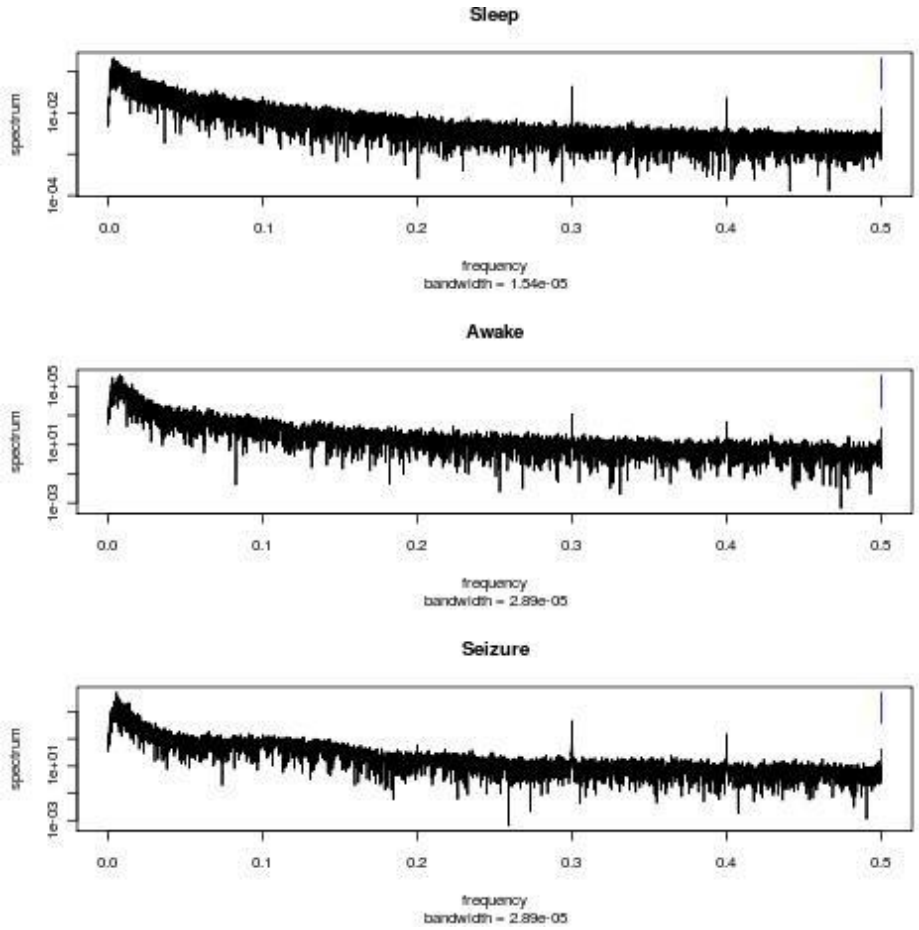
So, clearly the average distance between the distinct waveforms is highest for seizure, lowest for sleep with awake in the middle. This backs up the PCA result.

The PCA for sleep shows that there is effectively only one "signal" across the 64 channels. You can easily construct a linear model (through simple ols regression) of any of the individual channels based on a small number (< 10) of the other channels, and by doing this you will recover 99% of the channel. Awake is similar but less extreme, there is one dominant signal but there is some differentiation, while seizure still has a dominant signal the PCA shows it is much less influential and there are

several other signals present in the telemetry. In info-theory terms, sleep has minimum entropy, awake next, and seizure has highest entropy by a long way.

THE MAIN FINDING IS THAT THERE IS NO SINGLE DOMINANT FREQUENCY IN ANY OF THE DATA SETS.

To describe any of this telemetry as having a "carrier wave" is inaccurate. A mean of the inverse of the period of the positive zero-crossings can be calculated for each state; however that is not a "carrier wave". A typical spectral analysis plot shows that there is no dominant frequency structure. The spectrum analysis shows that the dominant signal in each data set does not decompose into a small number of frequencies, but rather, as one can see from the plots, observes a gradual, roughly linear fall off in power with increasing frequency;



DISCUSSION AND FURTHER RESEARCH

In a recent NY Times article (Zimmer, 2010), Tononi chooses to propose a rather sketchily-described "Shannon informational" model to supplant a gamma synchrony model partly on these grounds;

> "Dr. Tononi sees serious problems in these models. When people lose consciousness from epileptic seizures, for instance, their brain waves become more synchronized. If synchronization were the key to consciousness, you would expect the seizures to make people hyperconscious instead of unconscious, he said..... Consciousness, Dr. Tononi says, is nothing more than integrated information. Information theorists measure the amount of information in a computer file or a cellphone call in bits, and Dr. Tononi argues that we could, in theory, measure consciousness in bits as well. When we are wide awake, our consciousness contains more bits than when we are asleep."

Jouny et al (2010) surely should have suggest that this is premature closure, with an INCREASE in signal complexity – that is, decline in synchrony – associated with seizure. We too have found, contrary to Tononi, that seizure is a complex state in informational terms. In an attempt to give broad latitude to possible counter-arguments, it is worth noting that our work responds to Tononi's call to measure neural processes in bits. Information, entropy and signal complexity are deeply interrelated in any schema in this area; it is nonsense to suggest a la the queen of Tarts that we can redefine these words to make the "integrated information" schema work.

Secondly, it is indded possible that future work will resolve observation at a finer grain than current ECOG/LFP. All arguments above still hold; what is being measured in the information/entropy/signal complexity over a neural system. We intend further to analyze the heat maps involved to derive further patterns.

University of Ireland
President@universityofireland.com

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