Resting state EEG functional connectivity dynamics as diffusion in an attractors' landscape. Implications for modeling the aging brain.

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Functional relationships among brain signals as recorded by neuroimaging methods (EEG, MEG, fMRI) at rest open a window into the functional state of the human brain. In particular, resting state functional connectivity (rsFC), in the context of fMRI, is used as a neuromarker of disease, development, and aging. However, it hasn't been possible until now to embed rsFC into a context that can combine theoretical predictions and multimodal neuroimaging. One major limitation is that FC is conventionally averaged over long time series under the strongly questionable assumption of data stationarity. Indeed, recently attention has been drawn to the rich transient dynamics of such functional relationships, i.e., either functional connectivity dynamics (FCD) for fMRI [1], or synchronization dynamics (SD) for EEG [2]. In particular, rsFCD has been described as a "switching" dynamics: it sequentially explores different subspaces of its original high-dimensional space, transiting rapidly among them, and driven by noise [3]. Building on this result, we propose a "toy-model" for this "switching" rsFCD as a diffusive exploration of an attractor landscape based on the following analogies: the state variable of the model, x, stands for the high dimensional state space of FCD, and the attractors correspond to different subspaces that FCD explores. The "switching" dynamics is controlled by two parameters that stand (a) for the ratio between the deterministic phase flow and uncorrelated, Gaussian noise (parameter s), and (b) for the "richness" of the dynamical repertoire of the model (parameter R), implemented as the density of the attractors in the unbounded, one-dimensional, state space. We simulated the model scanning this two-dimensional parameter space, and calculated the statistics of the "jump lengths", i.e. the displacements $x(i) - x(j)$, for different time scales $\tau = t(i) - t(j)$, where t stands for time. We fitted parametrically the resulting jump length distributions (JLDs) across scales as alpha stable distributions and observed that (a) for very small values of stability (s) as well as for extreme values of the richness R (either for very small or very large values), the dynamics of the model resembles Brownian motion, and the respective JLDs are normal (stability parameter α approaches the value 2), (b) in between these extreme cases JLDs diverge from normality and exhibit fat tails ($\alpha<2$) In the case of normal JLDs we observed a lack of "switching" dynamics, either because the system is trapped in a single attractor's basin, or because it transits in a completely uncorrelated manner between neighboring attractors that are too dense, too unstable or both. Instead, JLDs diverge from normality when transitions among attractors or "jumps" within attractors can be actually differentiated, leading to "switching" dynamics endowed with long-range correlations. We propose that this parametrical region corresponds to the experimentally observed rsFCD. In this region, the dynamics is characterized by a time scale separation between the time of exploration of a particular subspace of the FC, and the time needed to transit to another distinct one, as well as by an equilibrium between stability and flexibility of the dynamics. Indeed, applying the method to both fMRI and EEG experimental rsFCD data showed that they exhibit a divergence from normality with α values similar to the model's ones. Finally, we discuss the implications for the aging brain in the context of recent studies that evaluate changes in the magnitude and structure of neuroimaging signals' variability with age. We suggest that well known degenerations of the aging brain, such as the dysfunction of the dopaminergic system, or white matter alterations like demyelination, can lead to alterations in the brain's exploration of its dynamical repertoire at rest. The former degenerations have been suggested to decrease the signal to noise ratio in the brain, whereas the latter can modify brain's dynamic landscape, resembling the effect of the two parameters of our "toy-model". Thus, stochastic qualifiers of such degenerations might result from the ideas presented here.

References

[1] R. F. Betzel, M. A. Erickson, M. Abell, B. F. O'Donnell, W.P. Hetrick, O. Sporns, Synchronization dynamics and evidence for a repertoire of network states in resting EEG, Frontiers in Computational Neuroscience, 6(September), 74, 2012.

[2] V. D. Calhoun, R. Miller, G. Pearlson, T. Adali, The Chronnectome: Time-Varying Connectivity Networks as the Next Frontier in fMRI Data Discovery, Neuron, 84(2), pp. 262-274, 2014.

[3] E. C. Hansen, D. Battaglia, A. Spiegler, G. Deco, V. K. Jirsa, Functional Connectivity Dynamics: Modeling the switching behavior of the resting state, NeuroImage, 105, pp. 525-535, 2014.