Energy landscape analysis of age-related changes in the human brain

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Executive cognitive functions of humans are known to decline with aging. Such functions are considered to be generated by well-coordinated activity patterns of neural signals in the brain. In the present study, we applied the so-called energy landscape analysis (ELA; schematically shown in Fig. 1) [1, 2] to resting-state fMRI signals obtained from healthy younger and older adults [3] and analyzed activity patterns in the so-called default mode network (DMN) and the cingulo-opecular network (CON), each of which was specified by a particular set of regions of interest (ROIs). ELA binarizes the signal into $\sigma = -1$ (inactive) or $\sigma = +1$ (active) at each ROI at each time point (Fig. 1). If a network contains N nodes, the activity pattern at each time point is represented by one of the 2^N possible activity patterns, denoted by $\boldsymbol{\sigma} = (\sigma_i, \dots, \sigma_N)$.

The frequency of occurrence of each activity pattern is fitted by the Boltzmann distribution given by,

$$P(\boldsymbol{\sigma}) = \frac{\exp[-E(\boldsymbol{\sigma})]}{\sum_{\boldsymbol{\sigma}} \exp[-E(\boldsymbol{\sigma})]}, \tag{1}$$

where $E(\boldsymbol{\sigma})$ represents the energy of the Ising model for a spin configuration, $\boldsymbol{\sigma}$, and is given by

$$E(\boldsymbol{\sigma}) = -\sum_{i=1}^{N} h_i \sigma_i - \sum_{i=1}^{N} \sum_{j=1}^{N} J_{ij} \sigma_i \sigma_j. \tag{2}$$

Using this energy value, the dynamics of the activity pattern is mapped to the motion of a "ball" constrained on an energy landscape (Fig 1).

In both networks ELA revealed that two synchronized patterns (i.e., the pattern in which all the ROIs were active, s_+, and that in which all the ROIs were inactive, s_-) appeared most frequently, and that the duration of these activity patterns were significantly longer in the younger than older adults. To further analyze the dynamics, we defined the "attractive basin" of s_+ (s_-), denoted by b_+ (b_-), based on the energy values of the activity patterns calculated by ELA (Fig. 1). Other activity patterns were defined to be b_{others}. One of these five labels was assigned to each of the 2^N activity patterns.

We found that the transition rate between s_+ and s_- was significantly higher for the younger than older adults both in the DMN and CON. Next, we calculated the rate of peripheral transitions between b_+ and b_- that did not contribute to transitions between s_+ and s_- (i.e., the rate of transitions between b_+ and b_- subtracted by the rate of transitions between s_+ and s_-) . The peripheral transitions were more frequent in the older than younger adults in the DMN (but the difference was not significant in the CON).

We defined an indicator for the ease of transitions between s_+ and s_-, called an efficiency score, by the rate of transitions between s_+ and s_- divided by the rate of peripheral transitions. The efficiency score was significantly larger in the younger adults, in both of the two networks. We found that the behavioral performance of individuals was significantly correlated with the efficiency score at the CON in the younger adults and at the DMN in the older adults. These results support the hypothesis [4] that, differently from younger adults, older adults heavily rely on the DMN for cognitive functions rather than on the CON.

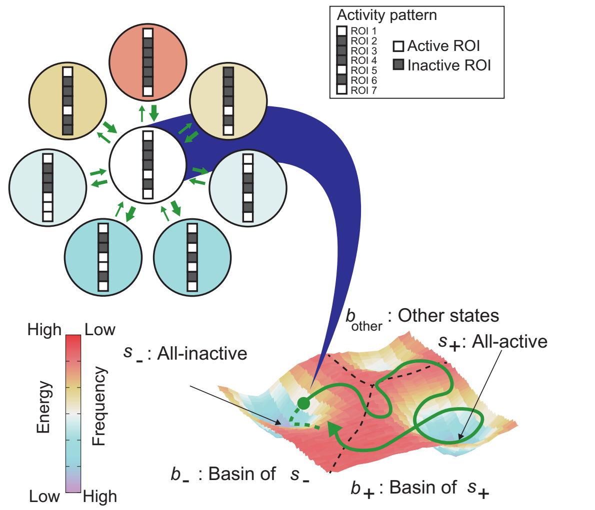

Figure 1: Schematic representation of the dynamics of the brain activity pattern constrained on an energy landscape.

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