Signatures of universal criticality in the anatomic structure of the brain

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Recent cellular-level volumetric brain reconstructions have given unrivaled access into the details of structures and connections in the brain, revealing an astronomical level of anatomic complexity [1-3]. A major challenge in analyzing this complexity is determining the structural aspects of the brain on which to focus when comparing any given brain with computational models and the brains of other organisms. Tools from statistical physics have provided powerful guidance in selecting and characterizing the key structural properties of a broad range of complex systems. Here we show evidence that such techniques can also be applied to quantify properties of the cellular structure of the brain.

We analyze partial reconstructions of human [1], mouse [2] and fruit fly [3] brains. The human [1] and mouse [2] datasets consist of roughly 1 mm^3 of cortical tissue, while the fruit fly (Drosophila melanogaster) dataset [3] includes roughly half of the fly central brain. We randomly sample subregions of each dataset and examine properties of cell fragments in each sample, including their size distribution and spatial correlations. We show that the organization of brain anatomy displays signatures of being poised close to a structural phase transition, or structural criticality, including fractal-like behaviour, broad size distributions and long-range pairwise and higher-order correlations. We obtain estimates for the corresponding critical exponents and verify that they obey the expected scaling relations, providing further evidence that brain structure is at or at least close to criticality. Moreover, we demonstrate that the values of the critical exponent estimates are consistent between the different organisms, which indicates that to first approximation brain anatomy may be described by a single brain structural universality class.

This framework enables extraction of relevant structural properties to study that are robust to many of the microscopic details of individual brains. This opens up the possibility of developing generative models within the brain structural universality class, from which further universal features of the brain could be inferred. Common structural features between brains may also be used to clarify the sense in which one animal brain can be considered a suitable model for another.

References

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[3] L. Scheffer, et al., eLife, 9, e57443 (2020)