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Comment

Beyond the anatomy-based representation of brain function Comment on “Topodynamics of metastable brains” by Arturo Tozzi et al.

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Tozzi and colleagues [32] propose a comprehensive and thought-provoking account of brain-mind functioning, invoking concepts and tools from algebraic topology to non-linear dynamics.

This commentary briefly discusses some issues related to the description of functional brain activity and, more specifically, to the choice of aspects of brain anatomy or physiology (reflecting at a macroscopic level neurophysiological phenomena not observable by system-level neuroimaging techniques) that should be used to define and describe functional brain activity.

1. Exploring the functional space

Often, in tumour removal procedures neurosurgeons operate on a sedated but awake patient to precisely locate functional brain areas that must be avoided. To do so, brain regions are electrically stimulated while the patient performs tasks such as talking, counting or looking at pictures. The patient’s responses are then used to create a functional map of the brain and remove as much of the tumour as possible. Neurosurgeons thus navigate into the space of cognitive function using the Euclidean space of brain anatomy, and some anatomo-physiological landmarks. However the anatomy-to-function map is not smooth, and the topology induced by local electrical stimulation non-trivial. So, how should stimulation be carried out, i.e. on what space should it act, to render the application smooth and the resulting topology “tractable”? Stated otherwise, how should the brain space be visited to make the functional space and its organization observable?

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Defining the functional space involves partitioning two separate, possibly multilevel spaces, respectively made observable by behaviour and brain recording techniques, imposing a structure upon the set of equivalence classes, and mapping the corresponding structures.

In most studies, the neurophysiological space is typically embedded into the anatomical space of classical neuropsychology and treated as a space of fields $\Psi = \{\psi_X(\vec{s}, t)\}$, endowed with the Euclidean metric. However, embedding an object into a metrical space may conceal important aspects of its structure [33]. Moreover, while at least at certain scales, there appears to be a relationship between anatomical structure and brain dynamics [12], at intermediate asymptotic scales [2] the properties of the functional space are likely independent of the underlying hardware [17]. As a result, although the Euclidean structure of the anatomical space may sometimes adequately reflect functionally relevant partitions at micro and mesoscopic scales, it is in general not a good description of the *functional space* organization at whole-brain macroscopic scales.

2. Beyond the Euclidean functional space

The functional space can be endowed with a task-related dynamical auxiliary space. Insofar as task-induced dynamics can be thought of as a selection of patterns present in spontaneous activity [18,22,30,5], to chart the functional space boils down to characterizing the *structure* induced on spontaneous brain dynamics by the impact of function. The structure of the neurophysiological space, i.e. its geometry, topology and symmetries, the way to parse it and, thence, the corresponding functional space are considerably more complex than is the case for the anatomical space of cognitive neuropsychology. For instance, experimental evidence shows that functional brain dynamics can live in complex spaces, e.g. in toroidal surfaces [14]. At long scales, spontaneous brain fluctuations are generically characterized by complex scaling properties [23,19,4,16,7,31,13,1] creating spatio-temporal structure within and between a wide range of scales [24]. The geometry induced by fluctuations turns out not to be Euclidean but fractal. Fluctuation probability distributions can be thought of as the points of a Riemannian manifold, forming a statistical manifold, equipped with the Fisher information metric. More generally, the phase space can be endowed with arbitrarily complex topological properties, e.g. those induced by a network representation [9], and functionally relevant symmetries and symmetry groups can be identified not only in the anatomical space, but also through the symmetries in the system output, e.g. in the phase space of ordinary differential equations [15], or in functional network structure [27], and more generally, in the structure defined on the functional space [25,26].

To achieve robust functionally meaningful descriptions, it may be useful to represent the neurophysiological space as a space that does not derive its topology from a metric, and to resort to representations that are non-local in the anatomical space [3,28]. Ideally, one would want to frame the functional space as a general non-metric one, and brain function in terms of stability conditions of some robust invariant with respect to the model (including scale) of brain description. Such spaces would allow treating the multiplicity of observables, observation scales and geometries by constructing summaries over whole domains of parameter values. They would also allow defining relationships between geometric objects constructed using different parameter values, and continuous maps relating these objects [10]. For instance, experimental evidence [20,29,8,6,11,34] suggests that the functional space maybe partitioned into universality classes, and that cognitive demands may operate transitions between them [21]. The requirements of given tasks would then act on the functional form and symmetries of brain activity rather than on its amplitude or frequency, inducing cross-overs between universality classes, with renormalization flows constituting generalized dynamic pathways within the functional space [25].

One would also like to have a criterion to decide whether any two observed states are distinguishable and to establish whether one state can be transformed into another under some dynamical neurophysiological process. A Euclidean space in principle provides metric criteria for distinguishability and distance between observed brain states, but distances in the anatomical space do not necessarily correspond to functional distances. On the other hand, while in a complex space proper distances may not be defined, it may still be possible to define nearness and neighbourhood. A robust dynamical notion of these properties in the observation space should reflect the *accessibility* structure at microscopic unobservable scales, i.e. the configurations accessible from given ones through the dynamics of physiological processes. The true accessibility structure can only be revealed by functional projections onto an appropriate auxiliary space: insufficiently unwrapped spaces may have complex or not well-defined topologies, making comparisons of configurations arduous.

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