The Synapse: Intercollegiate science magazine

Volume 38 | Issue 1 Article 12

12-1-2023

The Neural Manifold: Unfolding the Matrix of Our Brain

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The Neural Manifold

Unfolding the Matrix of Our Brain

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From as early as the mid-1950s, scientists from around the world began to micro-stimulate the brains of monkeys, cats, dogs, and rabbits to see if stimulating a brain with a low voltage would elicit an action. German scientists found that monkeys and cats would walk faster when they micro-stimulated the motor cortex. Surprisingly, they found that the amount of voltage was positively correlated with the walking speed of the experimental animal.

Around the late 1900s, scientists started to develop probes that could be stuck into certain parts of the brain to observe action potentials created by the neuron. This led to an era of scientists recording brain activity through different tasks. In the early 2000s, the prevailing theory for how the brain encoded information was that each single neuron encoded one single piece of information. For example, if a person saw Jennifer Lopez, a neuron would fire, and then if the same person saw Taylor Swift, a different neuron would fire an action potential. This was the foundation of how scientists understood human cognition.

In 2013, scientists from Columbia University Stefano Fusi and Mattia Rigotti stunned the world when they discovered that each neuron does not have specific stimuli that elicit an action potential. Rather they exhibit mixed selectivity, wherein a neuron encodes more than one piece of information and exhibits selectivity over the information it encodes. "Higher dimensional representations can be produced by including neurons whose responses cannot be explained as a linear sum of aspect-related responses, that is, neurons with nonlinear mixed selectivity"

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This was derived from the idea that if humans had one neuron that encoded one piece of information, then they could only store a finite amount of information. Obviously, this was not the case, and the idea of mixed selectivity solved this problem. Thus, single-cell analysis of neurons became a base case for analysis rather than it being the main source for modeling.

However, analyzing single cells told scientists in neuroscience that each neuron could be projected onto a geometric plane based on their firing rates. Meaning, geometrically and crucially mathematically, each neuron would represent a single dimension. It became increasingly difficult to meaningfully analyze neurons with such high dimensional representations. This called for studying low dimensional representation of a neuron population.
The method to investigate the population dynamics through a low dimensional representation starts with Principal Component Analysis. PCA is a statistical technique used across all computational fields, utilized for dimensionality reduction. The technique works by identifying the most significant features in a dataset, which transforms the original data into a new set of variables called principal components. These components are ordered so that the first few retain most of the variation in a dataset. The more variation it covers, the better the model. Therefore, understanding the geometry of the neuron population has become one of the most unique yet important factors in studying, understanding, and analyzing information processing in the brain.

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One of the ways we can observe such geometric representations is through neural manifolds. A manifold, in a mathematical sense, is a collection of numbers, or points, that create a set. Similarly, a neural manifold is a structure that preserves certain identities of information encoded by neurons. The geometry of the neuron populations might show a clear difference in their manifolds based on their location.
Oftentimes, the manifolds will show up in random areas that can be only decoded with an overfitted line that separates the two manifolds; these variables are entangled. However, with the property of neural manifolds, it gives us the ability to separate information linearly. In a process called untangling, these variables that could once only be separated by an ambiguous line "disentangle" to produce a line separating the two different pieces of information. The mainstream analysis of neural manifolds has been focused on object recognition, speech classification, and abstraction of such variables. For example, Stefano Fusi showed that monkeys were able to abstract information of the stimulus, value, and action. He showed this by showing a neural manifold of different variations of tasks that were able to be disentangled through PCA.
Through techniques such as principal component analysis, dimensionality reduction, and the ever improving technology of brain recording technology, computationally analyzing neurons might give us the key insight into how our brain processes information. • • •