Information transfer in modular spiking networks

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Introduction

To interact with the external environment in real-time, cortical microcircuits must employ efficient and reliable mechanisms for passing information between different modules and for integrating input from multiple sources. Here we investigate, from a functional perspective, how structural features influence these mechanisms in the context of stimulus representation, integration and transfer in modular spiking networks.

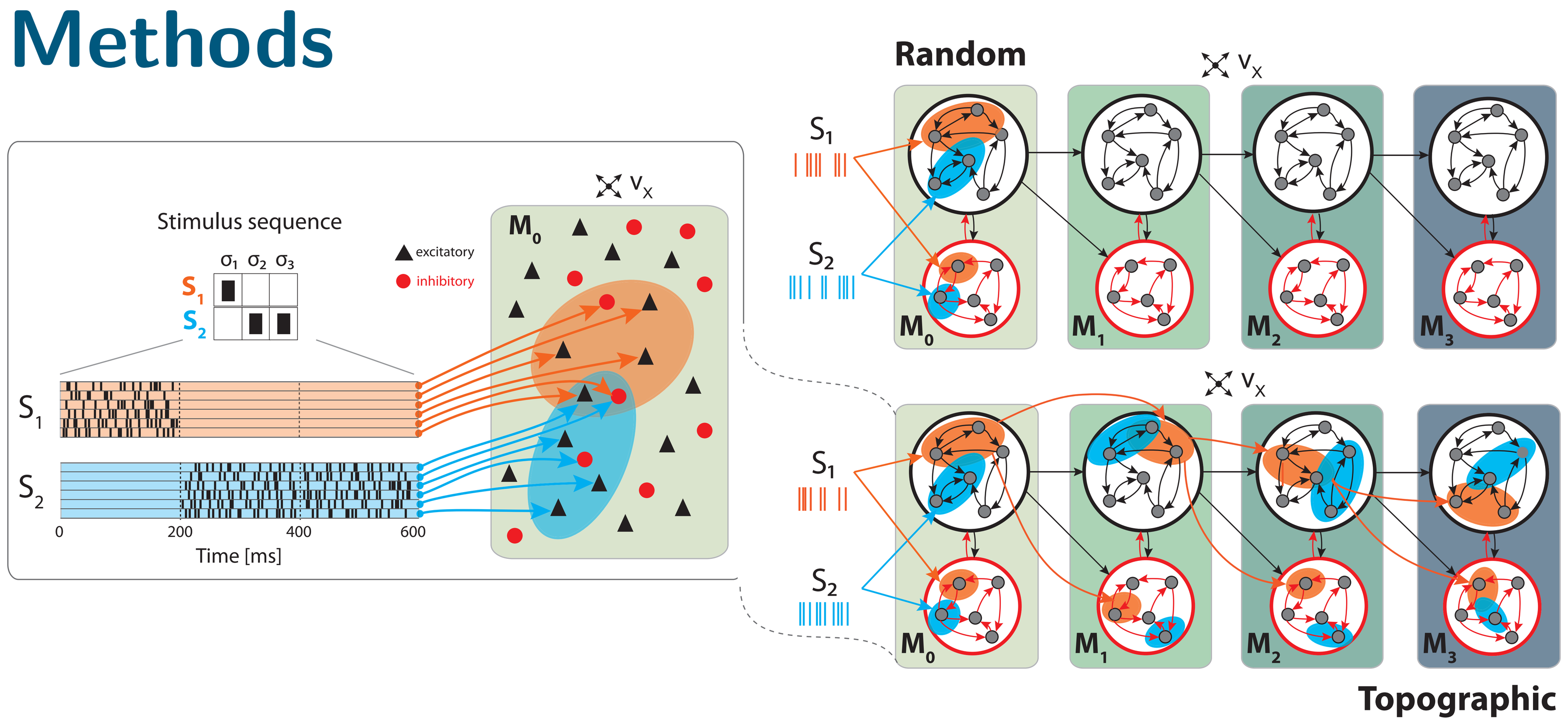
Hypothesis: biophysically-based architectural features (modularity and topography) impose critical functional constraints on the reliability of information transmission, aggregation and processing.

Focus: random connectivity and biologically-inspired topographic maps. Such maps, comprising ordered projections among distinct neuronal populations, are an important and well-studied anatomical feature. However, their computational significance remains relatively unexplored.

Objectives

- compare dynamics and performance of random and topographic networks
- evaluate how structural parameters of topographic projections influence the systems' computational properties (e.g., modularity, map size and degree of overlap)
- investigate the ability of the modular circuit to extract, integrate and propagate information from two concurrent input streams in a nonlinear fashion

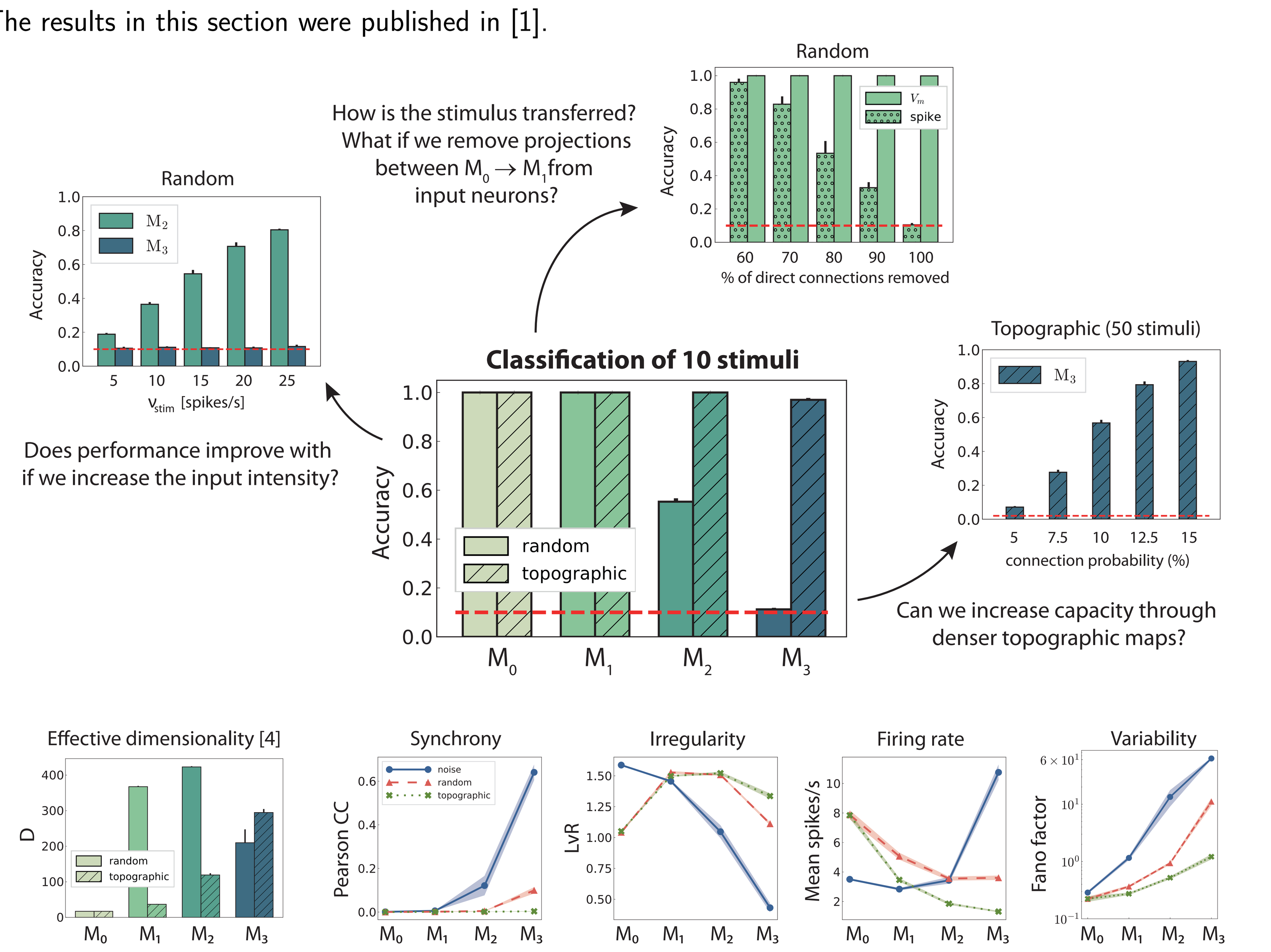
Methods



- Modules are balanced random networks (10000 leaky integrate-and-fire neurons)
- In networks with topographic maps, each stimulus is propagated through a specific pathway
- Structured stimuli drive specific, randomly selected sub-populations in M_0
- Treat local microcircuits as state-dependent processing reservoirs (Reservoir Computing) [2]
- Simple linear (classification of stimulus identity) and nonlinear (XOR) computational tasks

Sequential transmission of stimulus representations

The results in this section were published in [1].

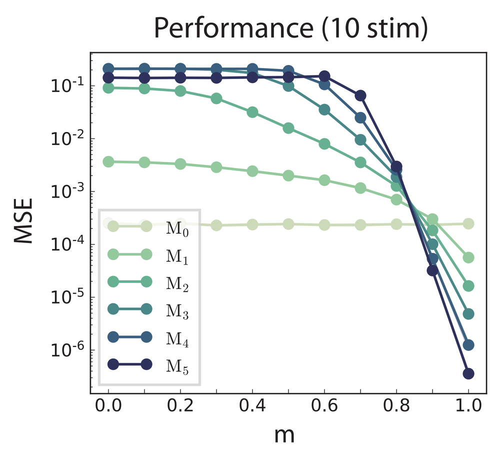


Structured projections are strictly necessary for information to propagate to sufficient depths.

- Random connectivity can be enough for local transmission
- Topography →
  - ⋆ asynchronous firing profile
  - ⋆ increased efficiency
  - ⋆ less variable responses
  - ⋆ more compact representations
  - ⋆ denser maps increase capacity

Impact of topographic map structure

Modularity

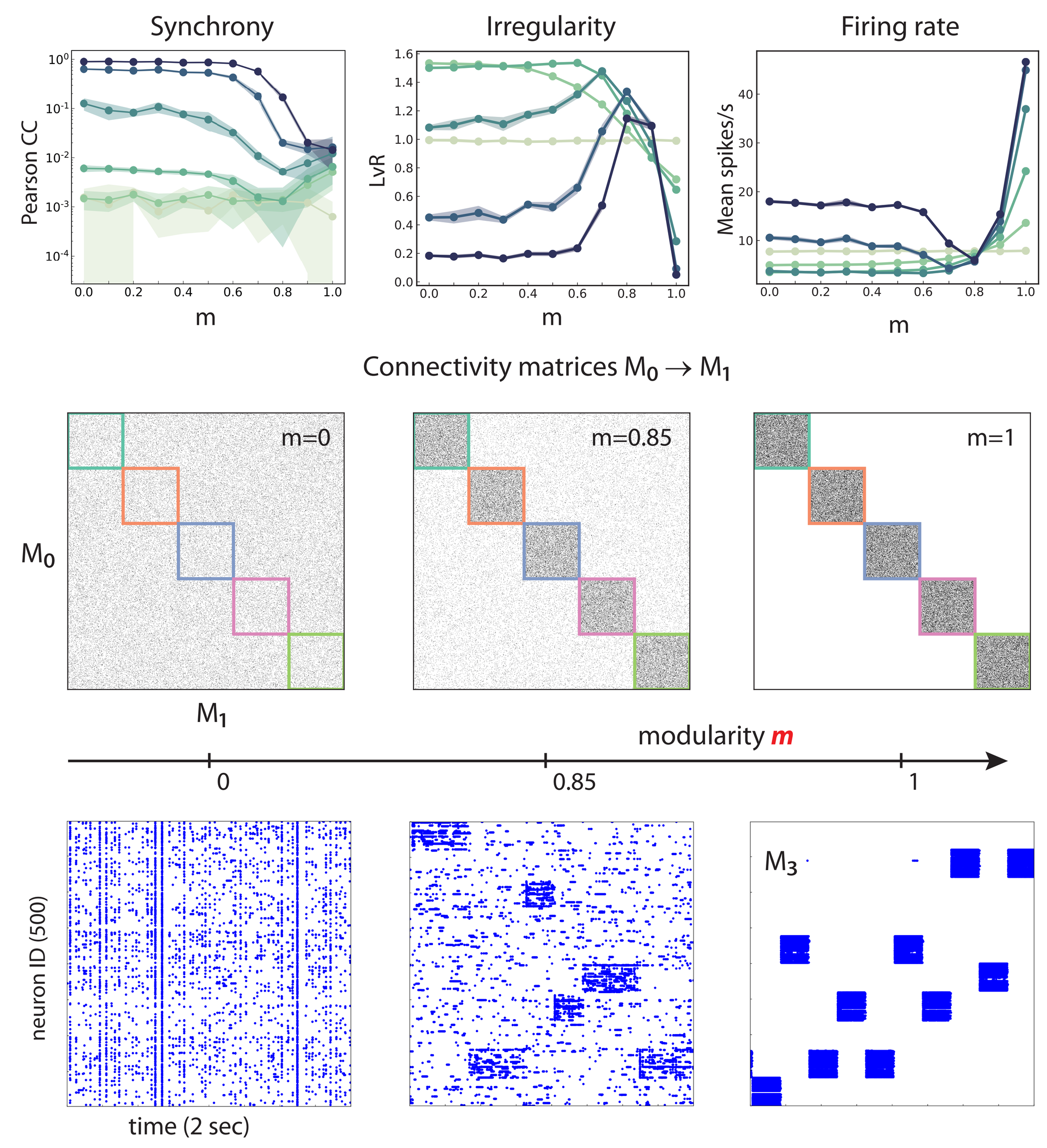


For structured feed-forward projections, define the topographic **modularity** m as

$$m = 1 - \frac{p_0}{p_c} \in [0, 1].$$

p_0: inter-cluster connection probability
p_c: intra-cluster connection probability

where cluster refers to the corresponding stimulus-specific sub-populations.

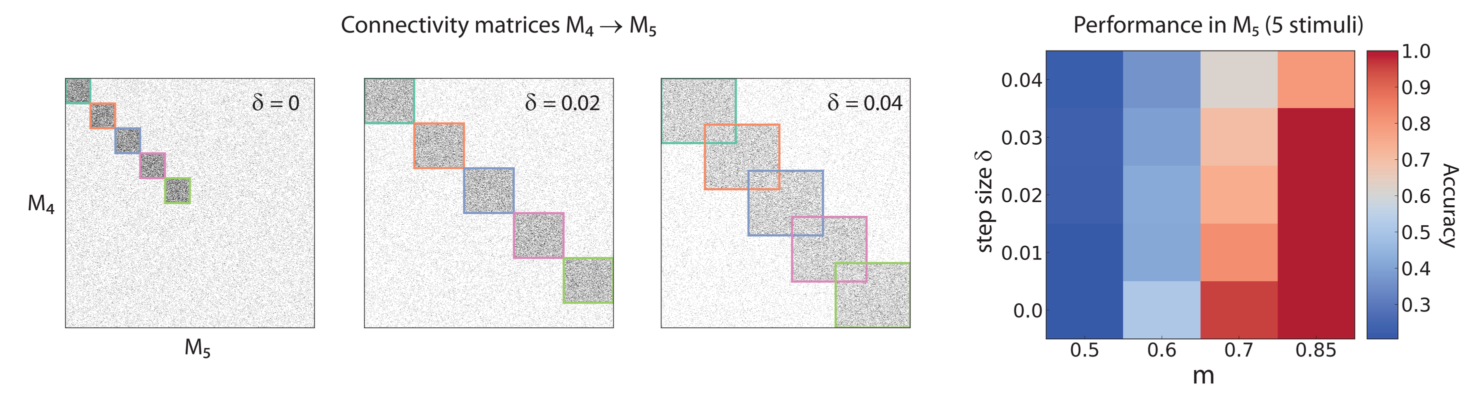


- Global population statistics converges towards a stable asynchronous irregular regime
- Networks exhibit denoising properties
- Overall discrimination capability improves with hierarchical depth

Topographic precision might be important for the control and modulation of population responses towards computationally advantageous regimes.

Map size and overlap

Topographic specificity in cortical networks is assumed to decrease with hierarchical depth [3]



- Increasing the map sizes linearly decreases *discrimination* performance
- This occurs even when there is no overlap
- For other tasks / computations mixing representations might be beneficial and necessary

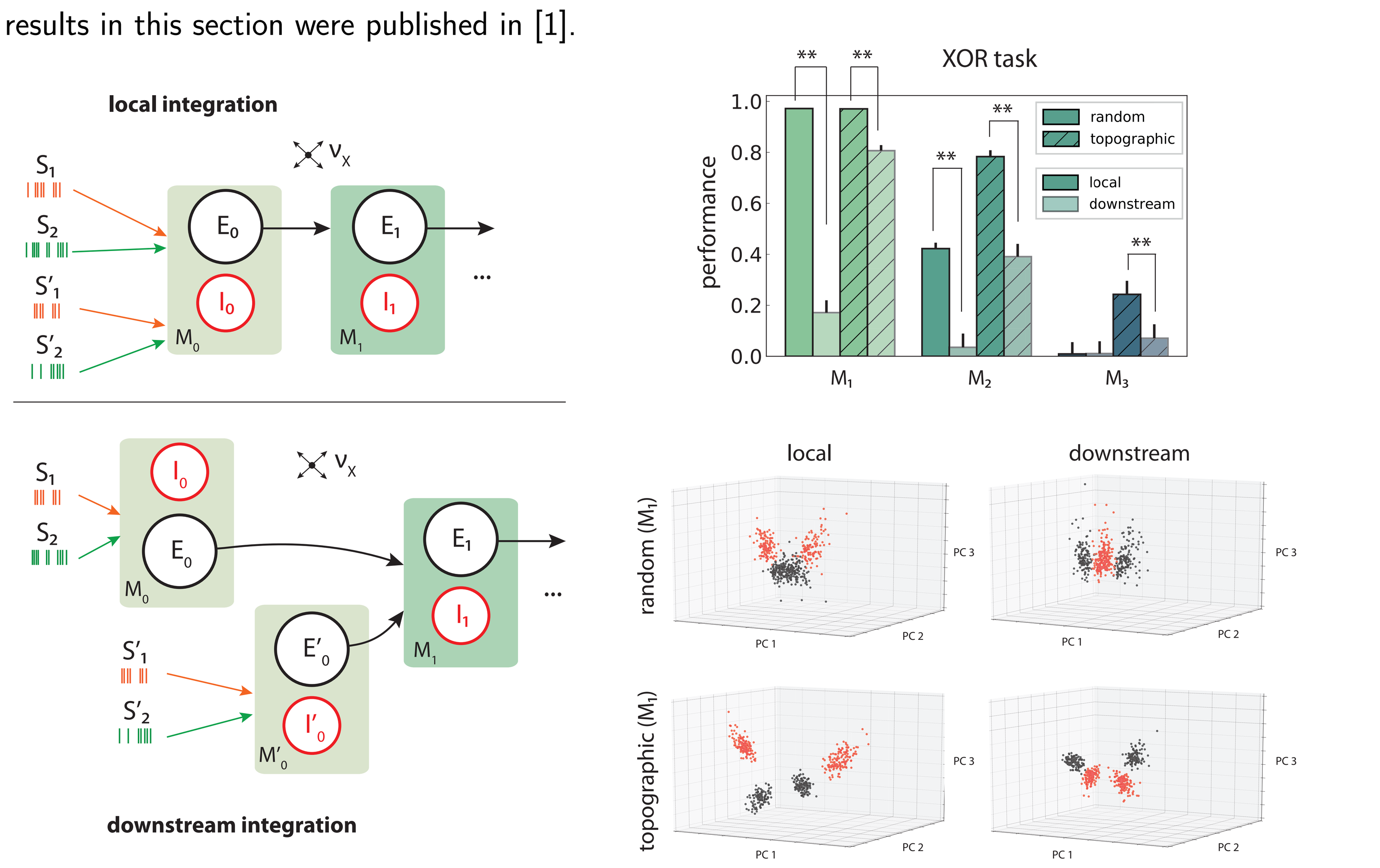
The map sizes are controlled by the scaling factor ρ

$$\rho^i = \rho^0 + i\delta, i = 1, \ldots$$

where $\rho^0 = 0.1$ is fixed and δ is the step size.

Integrating multiple input streams

The results in this section were published in [1].



Computing locally, within a module, and transmitting the outcome of such computation (local integration) is more effective than transmitting partial information and computing downstream.

- Topographic networks and local integration increase representational precision

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