Quantifying neural information content: A case study of the impact of hippocampal adult neurogenesis through computational modeling

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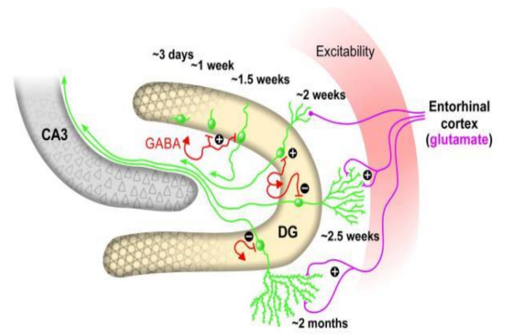
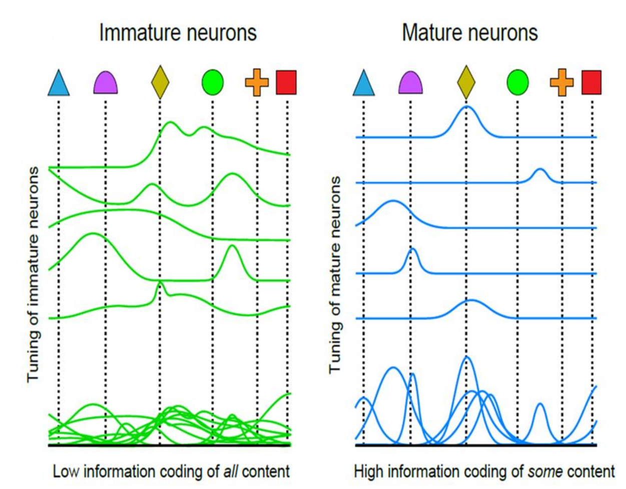
Background and Approach

Overview of Adult Neurogenesis

- 1000s of new granule cells integrate into DG monthly
- Only excitatory neurons are born; no new inhibitory neurons in DG
- Process heavily regulated by behavior; for example, running and enrichment increase, stress and aging decrease
- Maturation process extends over months, excitatory and inhibitory pathways develop in parallel
- Young neurons are more "excitable" than mature counterparts due to distinct physiology and connectivity



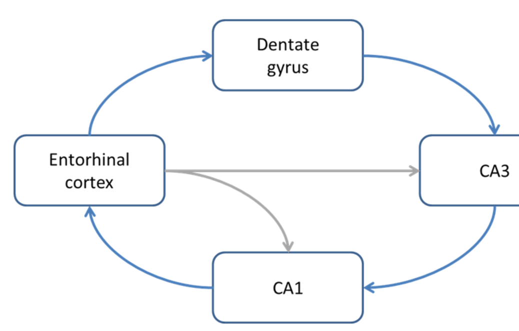


Aimone, Deng and Gage Neuron; 2011

Hippocampus Function

- Proposed to enhance the encoding of new memories by performing pattern separation
- Orthogonalization

- Primary input to the hippocampal formation
- Grid cell encoding

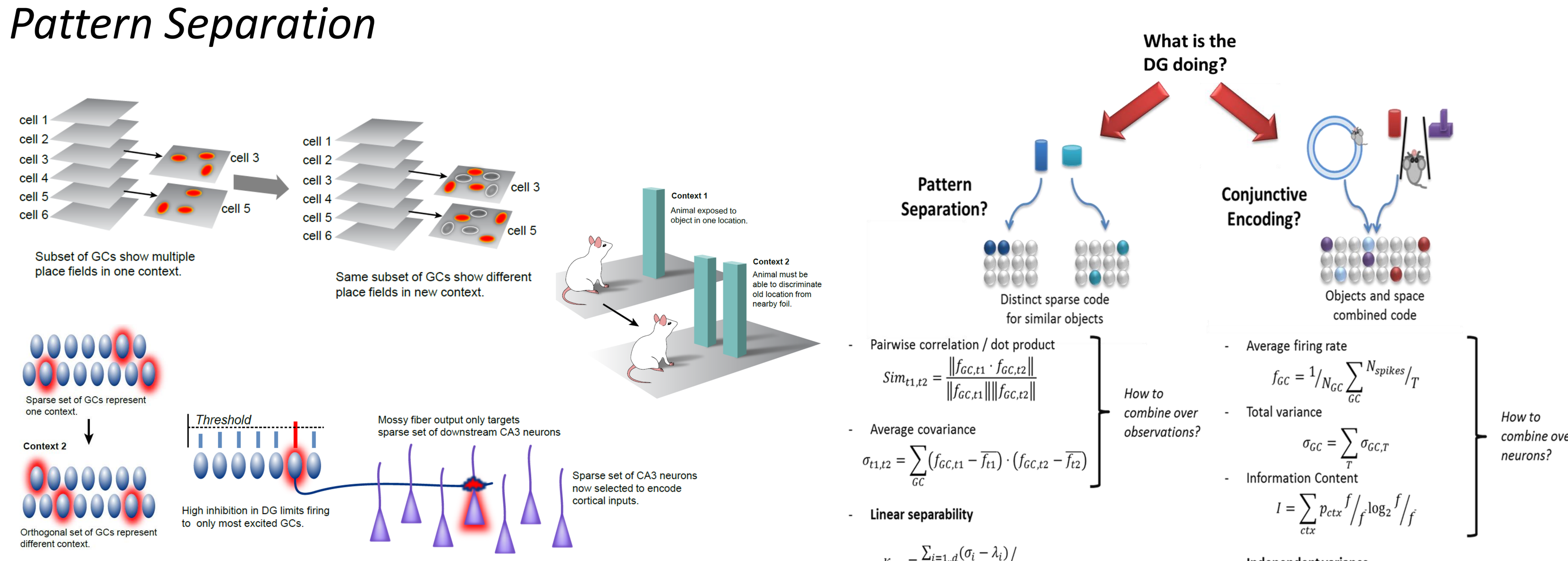


- Autoassociative encoding of input patterns
- Pattern completion

- Comparator of the input from EC with the output from CA3

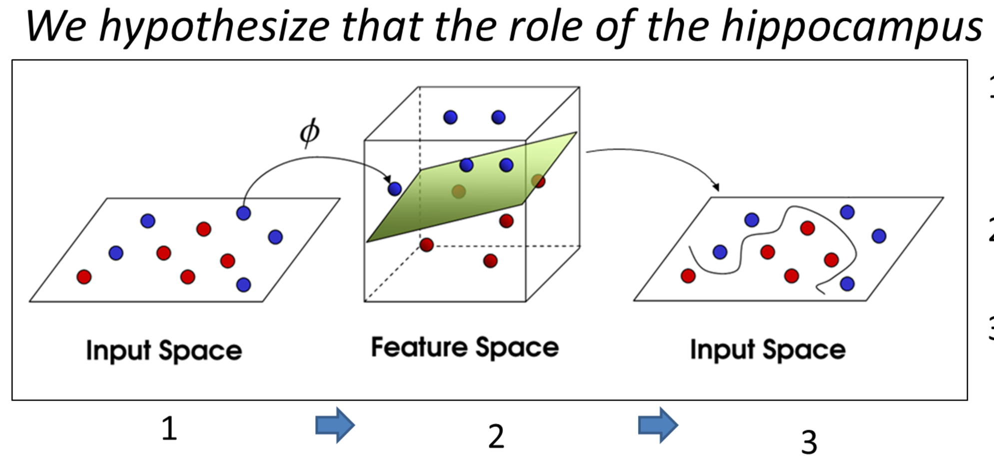
*Scholarpedia Function of Hippocampal subregions

Pattern Separation



Aimone, Deng and Gage Neuron; 2011

We hypothesize that the role of the hippocampus in information processing is:



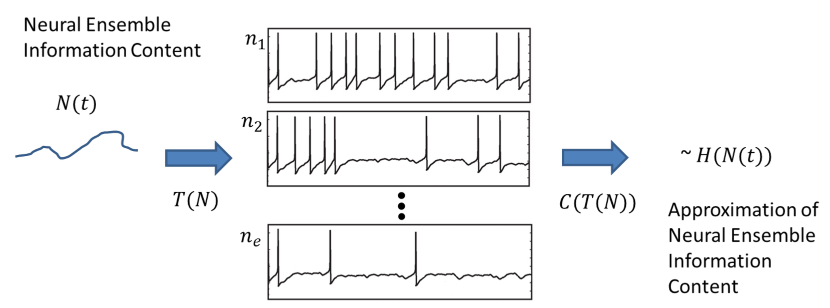
1) to restructure and refine the multimodal associative encoding provided by the entorhinal cortex (EC)
2) through a high dimensional adaptive transformation in dentate gyrus (DG)
3) and subsequent compressive encoding by the CA3

Analysis Methods

- Information theory provides entropy of a discrete random variable as a quantitative measure of information

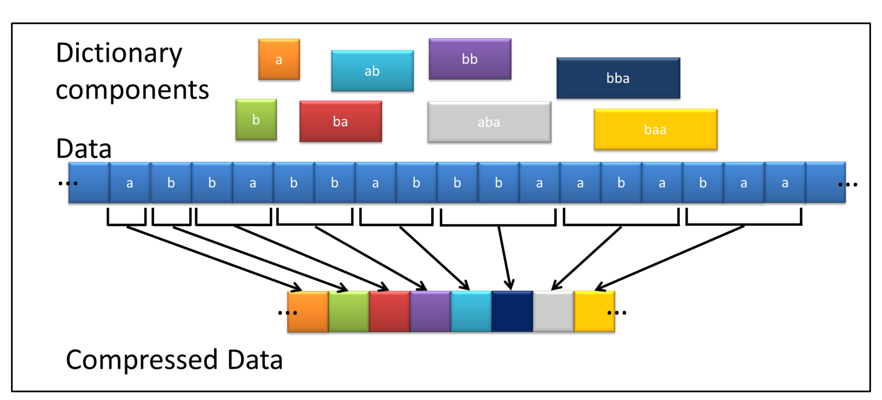
$$H(X) = \sum_{x \in X} p(x) \log\left(\frac{1}{p(x)}\right)$$

- Can be applied to neuroscience to quantitatively measure the information content of firing neurons
- And it has been with various methods such as (not a complete list):
  - Plug-in Entropy
  - Jackknife debiased
  - Asymptotically debiased
  - Ma bound
  - Bayesian/Dirichlet prior
  - Coverage-adjusted
  - Best upper bound
- But there are issues…
  - Entropy (and many other concepts from information theory) calculations require knowledge of the firing behavior probability distributions for the neurons - however
    - Limitations to in vivo recording capabilities
    - Neurons are somewhat deterministic
    - Neural plasticity effectively creates non-static distributions
    - Applied to single neurons but not ensembles

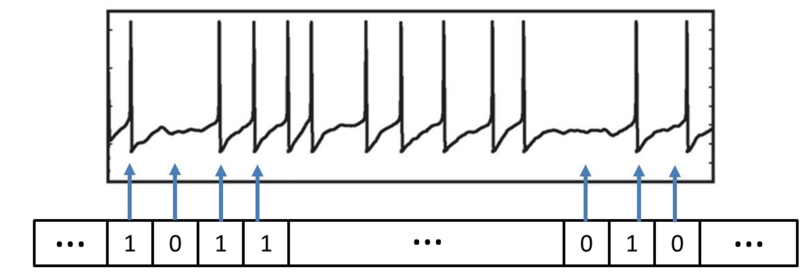


Compression

- Use complexity as a measure of compressibility in order to estimate entropy to quantitatively assess the information content of a signal
- Szczepanski et al. applied the general Lempel-Ziv complexity (LZ-Complexity) measure to estimate entropy of real and simulated neurons
- LZ Compression is a dictionary technique that does not require a probabilistic model
  - Rather dictionary compression techniques exploit redundancies in the data
  - LZ compression has been used in applications such as UNIX compress command and GIF compression



- LZ-Complexity is based upon measuring the rate of generation of new patterns along a sequence of characters in a string being compressed
- Applied to neuron spike trains, this technique looks for repeated spiking behavior over time

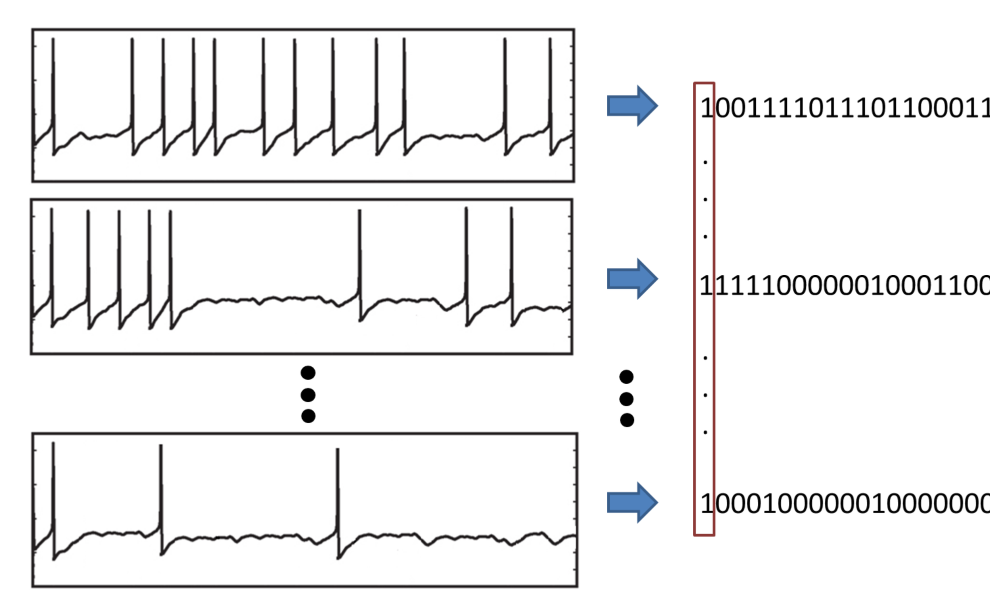


- Once the spike signal is converted into a binary signal, where an action potential is encoded as a one and the absence of activity by a zero, the normalized complexity may then be computed as follows:

$$c_\alpha(x^n) = \frac{C_\alpha(x^n)}{n} * \log_\alpha n$$

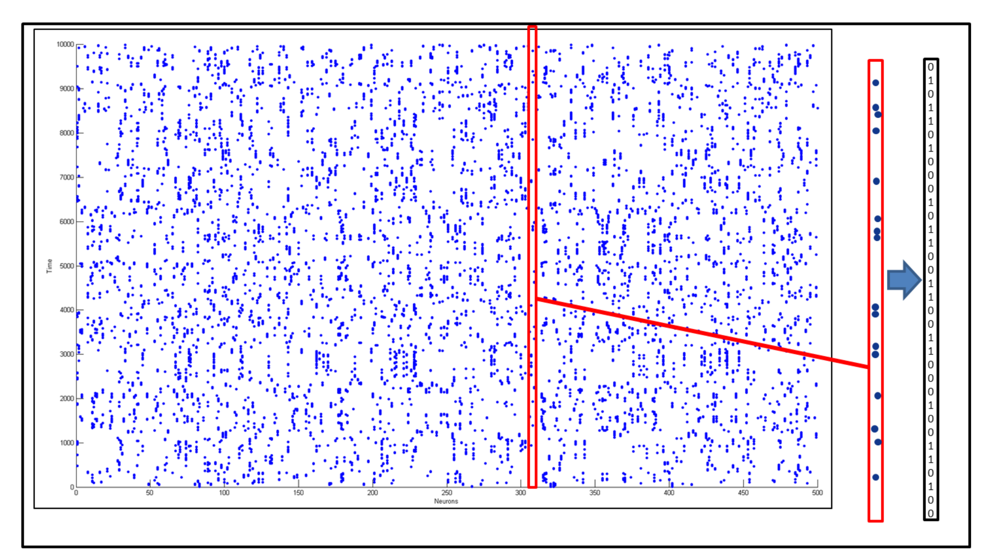
- Normalized complexity measures the generation rate of new patterns along a word of length n with letters from an alphabet of size α (in this case two)

- But unlike the work of Szczepanski et al., rather than applying LZ-Complexity analysis to individual neuron spike trains, we have applied the approach to a neural population as a whole
- Instead, by applying it across an entire neural ensemble, we assessed repeated patterns of neural co-activity



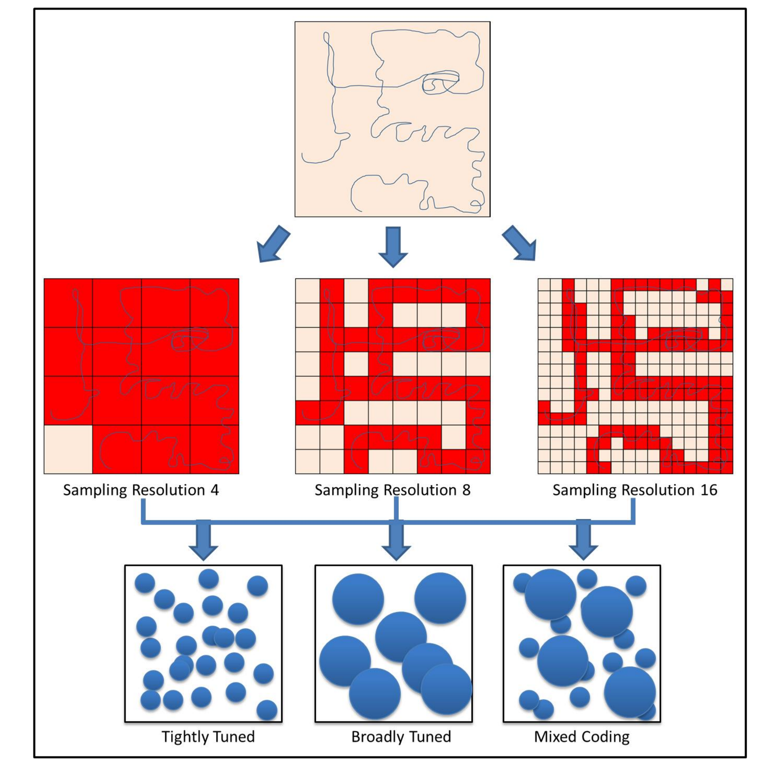
- It can be proven that as the string length (our series of neural firings in this case) goes to infinity, the supremum of the normalized complexity approaches the entropy of the signal S:

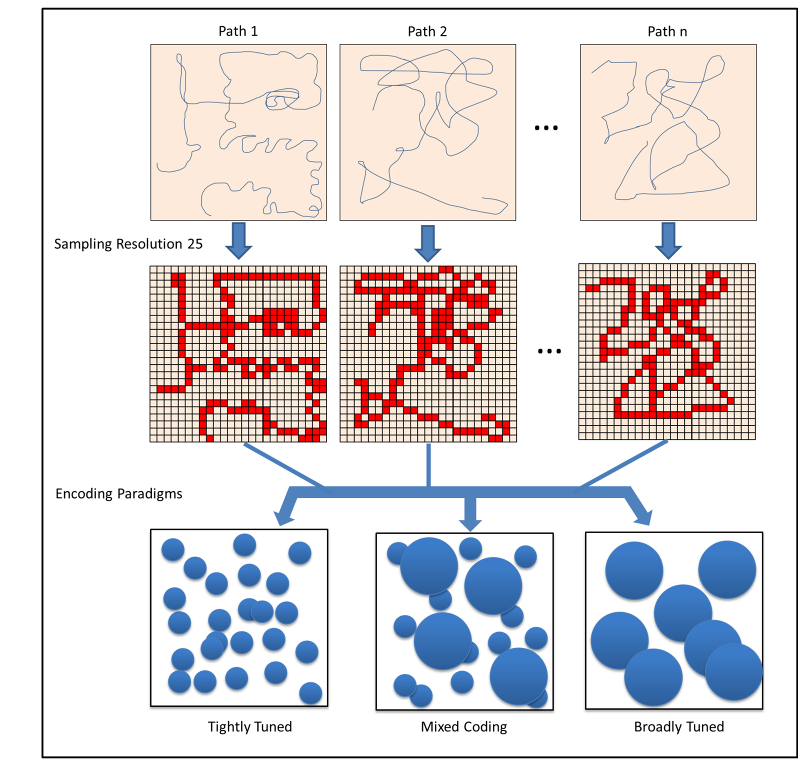
$$\lim_{n \to \infty} \sup c_\alpha(x^n) \le H_\alpha(S)$$



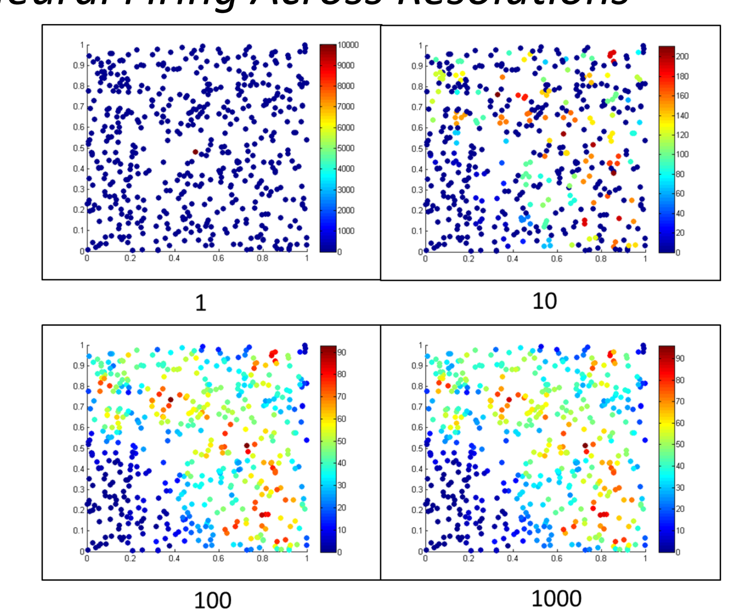
Results

Computational Paradigms

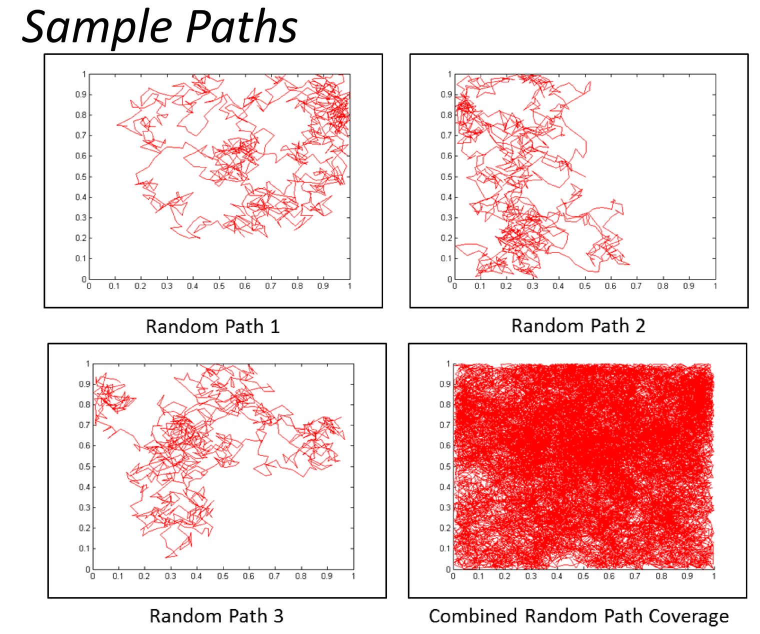




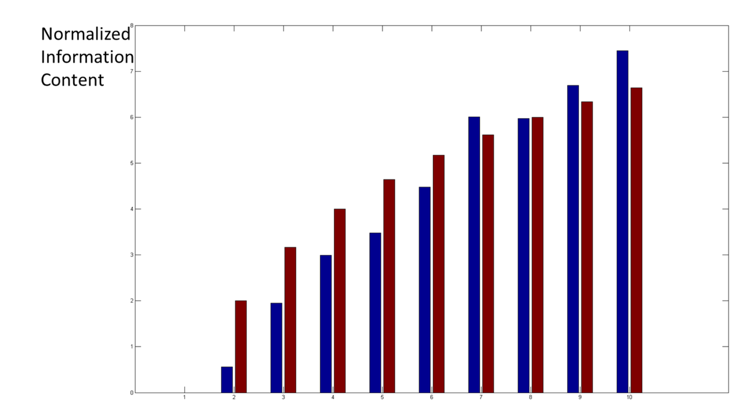
Neural Firing Across Resolutions



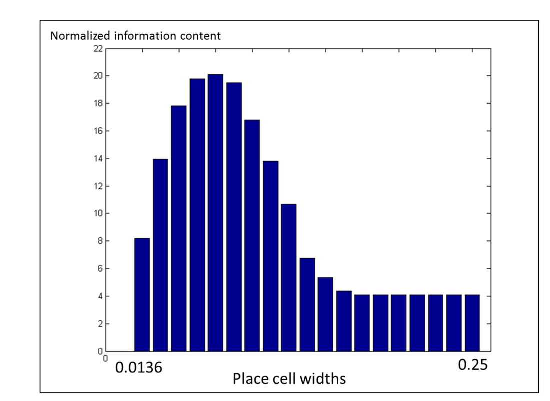
Sample Paths



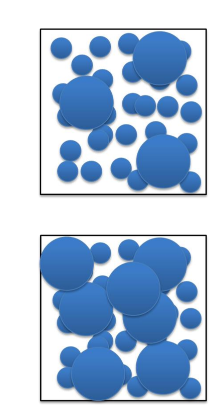
Resolutions 1-10



Exploring Place Cell Widths



Mixed Coding Analysis



10 % Mix Ratio – 100 Neurons Resolution 25

	0.0100	0.0233	0.0367	0.0500	0.0633	0.0767	0.0900	0.1033	0.1167	0.1300
0.0100	5.9559	6.7196	7.3064	7.7418	7.9513	7.9348	7.7806	7.5582	7.2862	6.9229
0.0233	11.8376	12.4588	12.9120	13.2711	13.4474	13.4236	13.2805	13.0811	12.8301	12.4988
0.0367	15.6965	16.2832	16.6958	16.9875	17.1077	17.0479	16.8820	16.6673	16.4103	16.0795
0.0500	18.1140	18.6909	19.0770	19.3526	19.4350	19.3490	19.1633	18.9282	18.6609	18.3250
0.0633	18.9772	19.5544	19.9337	20.1879	20.2609	20.1569	19.9554	19.7095	19.4361	19.0946
0.0767	18.3350	18.9188	19.2982	19.5461	19.6036	19.5014	19.2722	19.0193	18.7362	18.3870
0.0900	16.4977	17.0915	17.4734	17.7200	17.7725	17.6462	17.4234	17.1551	16.8637	16.5047
0.1033	14.0290	14.6394	15.0306	15.2815	15.3323	15.1964	14.9572	14.6821	14.3740	14.0053
0.1167	10.7681	11.4036	11.8135	12.0679	12.1104	11.9657	11.7076	11.4127	11.0858	10.6980
0.1300	7.1748	7.8600	8.2914	8.5696	8.6149	8.4560	8.1820	7.8634	7.5114	7.0811

Summary

- Present a metric & computational paradigm for quantifying neural information content
  - Case study - used this framework to study the impact of hippocampal neurogenesis
  - **Experimentally shown benefit to mixed coding**
  - Next investigate impact on CA3 network
- Present an alternative perspective on hippocampal function in information encoding & transformation
  - Implications for machine learning
  - Insights for neural computation

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