SAND2016-1788C

A Combinatorial Model of Dentate Gyrus Sparse Coding and Pattern Separation

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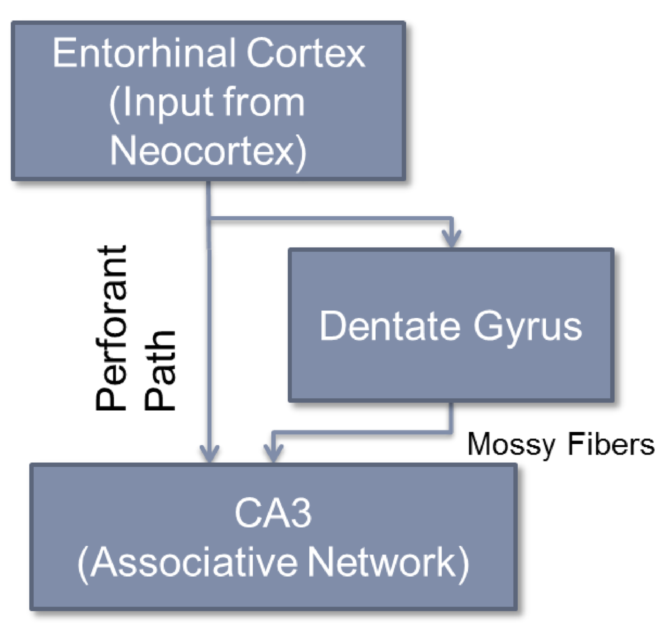
Background

Dentate Gyrus (DG) Supplies Sparse Input to CA3

- Two distinct paths to CA3 (associative network)
- Direct path is dense and weak—Used for recall
- Indirect path via DG is sparse and strong—Used for training
- DG readies information for CA3:
    - Lower correlations
    - Lower activity
    - Pattern separation
    - Redundancy
- DG sparse coding differences:
    - Closed form
    - Thresholding
    - Controlled Fidelity



Formulation

Subsets Act as AND Filters

Mapping: $F: \{0,1\}^n \to \{0,1\}^k$

Collection of Subsets: $\Delta = \{\eta_i : \eta_i \subset \{1, \dots, n\}\}, k = |\Delta|$

Coding: $F = fA$ with $A = [a_{i,j}]$ where $j \in \eta_i \Rightarrow a_{i,j} = 1/|\eta_i|$ or $a_{i,j} = 0$ otherwise, and f is the thresholding indicator function for $\{x \geq 1\}$

General Reduction: $\Delta = p -$ sized subsets of $\{1, \dots, n\}$

Formal Results

- Noise filtering around 0; Lossless for $\{|x| \geq p\}$
- Coding non-trivially decreases normalized correlations
- High redundancy, distributed outputs: If $||x|| = q$, then $\binom{q-1}{p-1}$ dimensions carry $F(x)$
- Action is never linear for non-zero inputs
- Outputs have assured minimum distance:

$$d(F(x), F(x')) = (q - r)\binom{q-1}{p-1} + (q' - r)\binom{q'-1}{p-1}$$

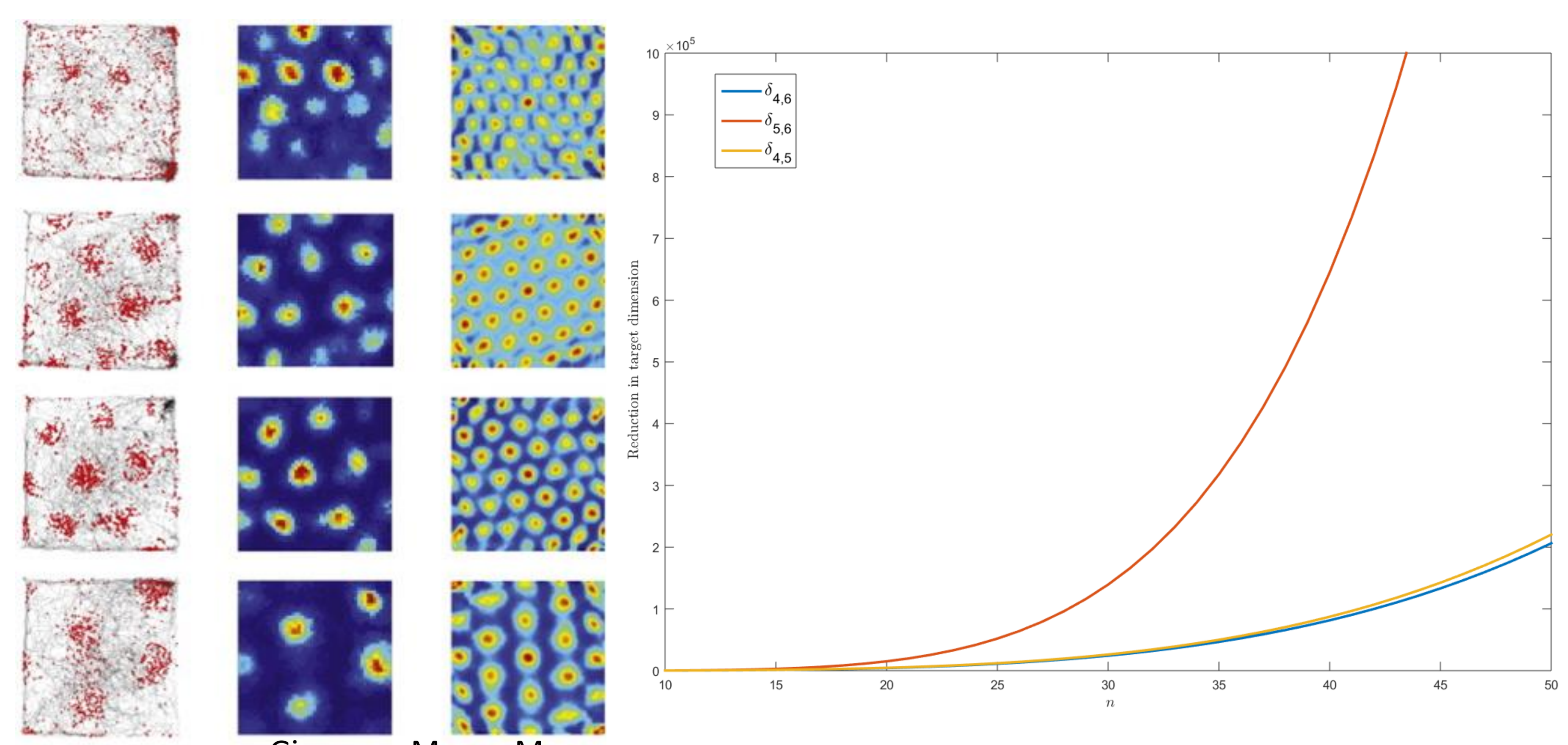
Grid Cell Refinement

Input Distributions Curtails Target Dimension Growth

- Allowing for the entire space $\{0,1\}^n$ yields unrealistically large k
- Knowledge of input distribution, allows refining Δ to match

Biologically-inspired Grid Cell Refinement

- Grid cells located in the Entorhinal Cortex encode spatial information using a modular code
  $$x \mapsto (x \bmod \lambda_i)_{i=1,\dots,T} \text{ for relatively prime } \lambda_i$$
- Action can interpreted as toroidal dynamics, connected via fundamental group
- Construct input space X group isomorphic to grid cell input; remove η_i from Δ if η_i never occurs



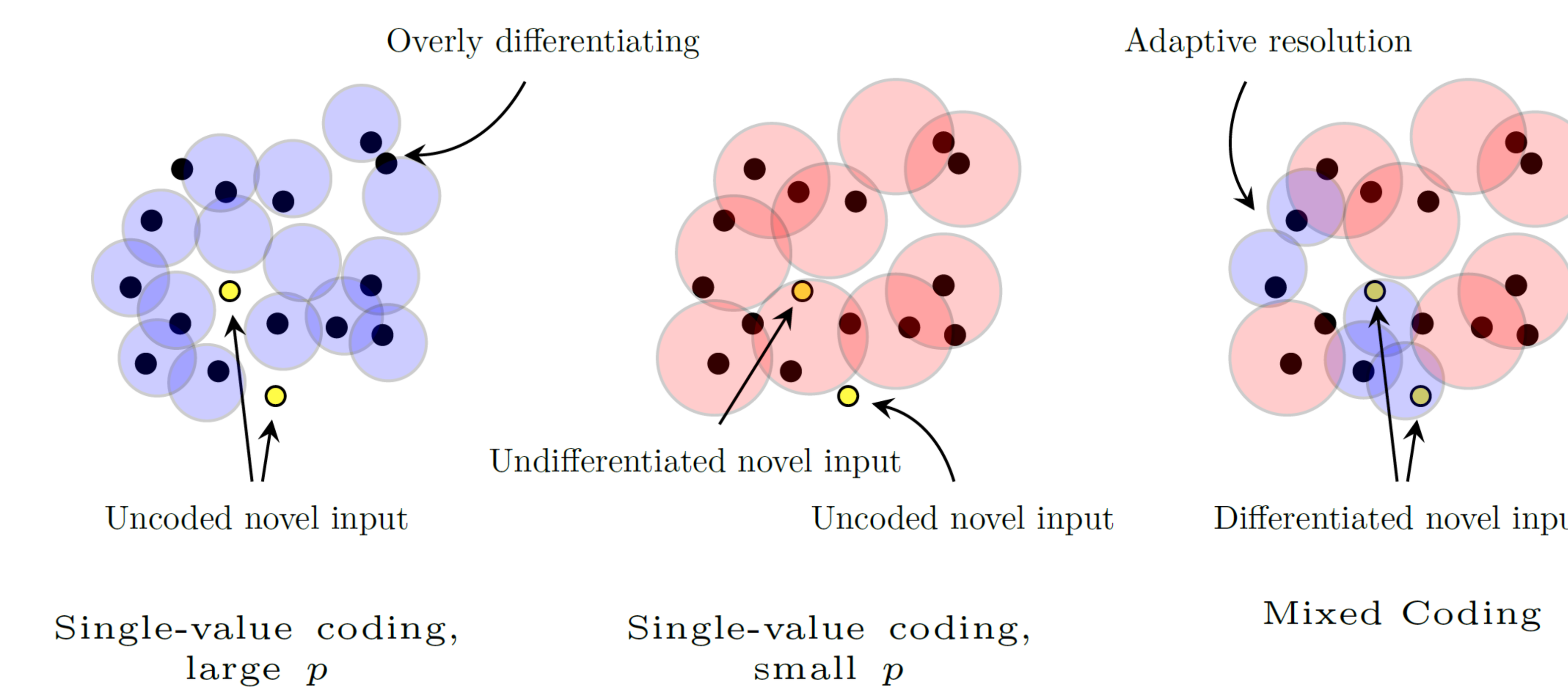
Giocomo, Moser, Moser

- Resulting target dimension k is minimal without data loss, estimated by
  $$k < \lambda_{max}^p \binom{T}{p} \leq \frac{n^p(T-1)\cdots(T-p+1)}{p!\,T^{p-1}}$$
- Using estimates for grid cell spacing in rats, model consistent with DG size
- Activity level satisfies requirement of Treves and Rolls

Mixed Coding

Adult Neurogenesis Improves Information Capacity

- Human DG develops new neurons throughout life
- Young neurons—Broadly tuned
- Old neurons—Tightly tuned
- Mixed coding allows for adaptive resolution, increased capacity



- Choose $\eta_i \in \Delta, p' < p$, expand
  $$\Delta' = (\Delta \setminus \{\eta_i\}) \cup \{p' - \text{sized subsets of } \eta_i\}$$
- Conditions exists to guarantee sparsity and decorrelation

Conclusion

Simple Combinatorial Models → Meaningful Behavior

- Theoretically-robust combinatorial code
- Formal results satisfy desired DG properties
- Code is adaptable to biologically-inspired inputs
- Grid cell refinement results match literature
- Mixed coding extensions mimic adult neurogenesis

Further Directions

- Incorporate rate coding beyond binning
- Connect to larger Hippocampus model
- Biology imparting constraints onto formalism
- Neural models via input/output requirements
- Abstract neural coding methods

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