Optimizing online learning capacity in a biologically-inspired neural network

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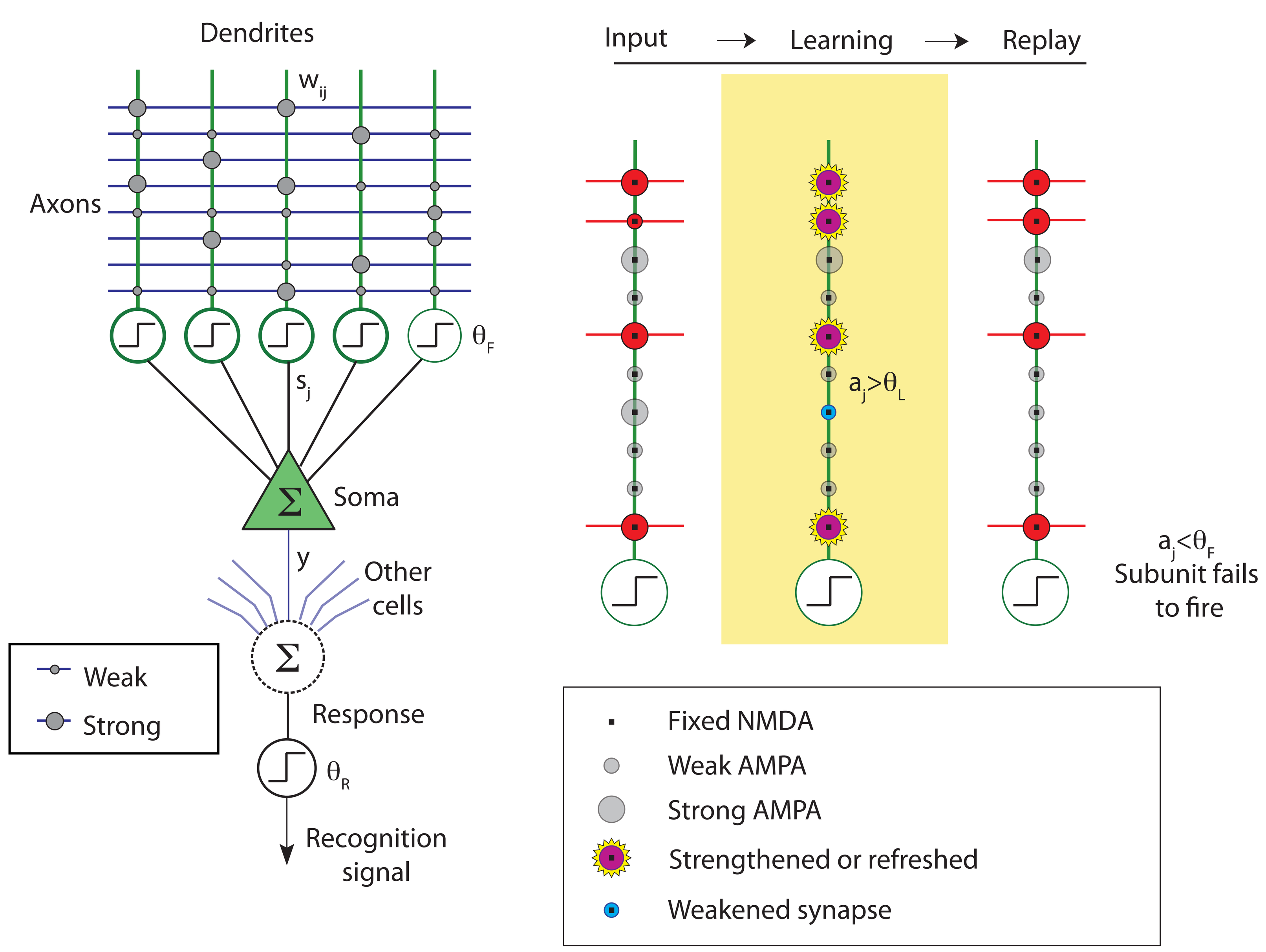
1. Introduction

To function in a complex world, our brains must somehow stream our life experiences into memory in real time as they occur. An "online" memory of this kind must be capable of forming durable memory traces based on single brief exposures to each incoming pattern, while preserving older experiences as long as possible. This need for near instantaneous storage and large storage capacity presents a huge challenge to our nervous systems, and we currently know little about how the process works in detail.

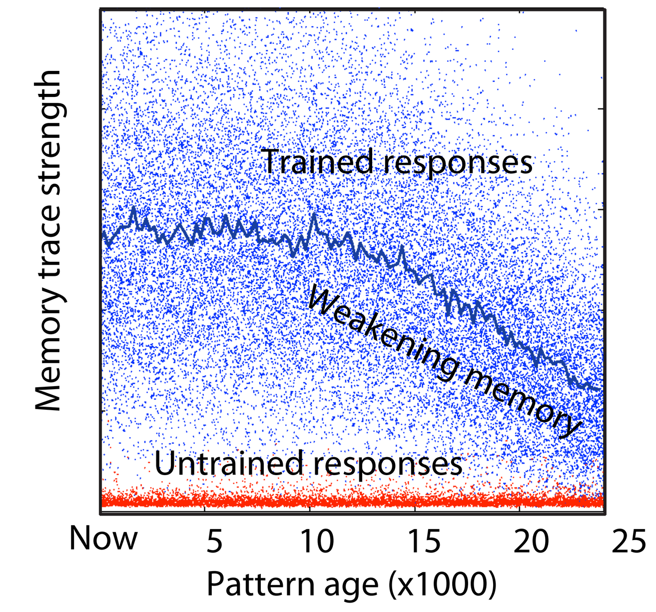
Using computer models and mathematical analysis, we have studied the online learning capabilities of a biologically-inspired network, with the goal to understand how neurons, dendrites, and synapses can work together to maximize online storage capacity. Based on experimental evidence from the last 20 years, a key assumption in our work has been that dendrites, rather than whole neurons, are the main signaling units used to store and read out learned information.

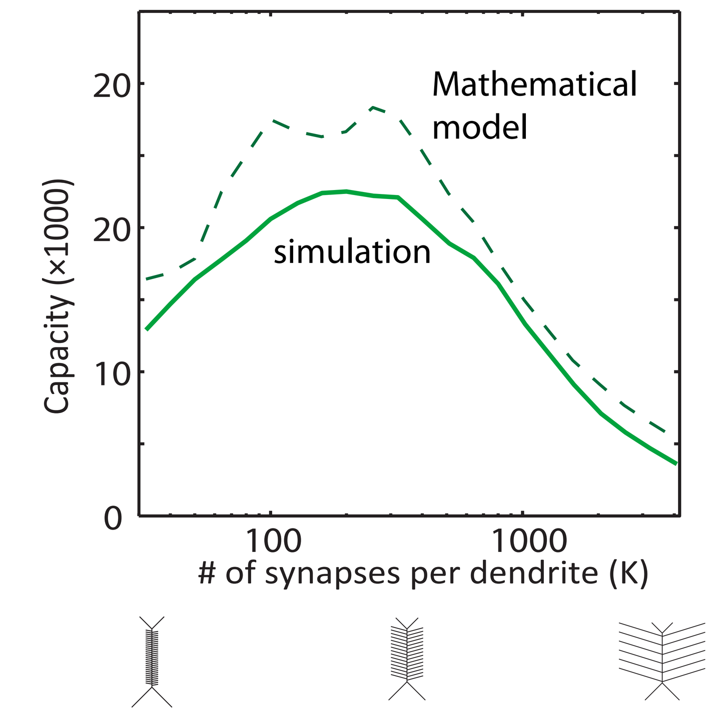
2. Model Architecture and Learning Rule

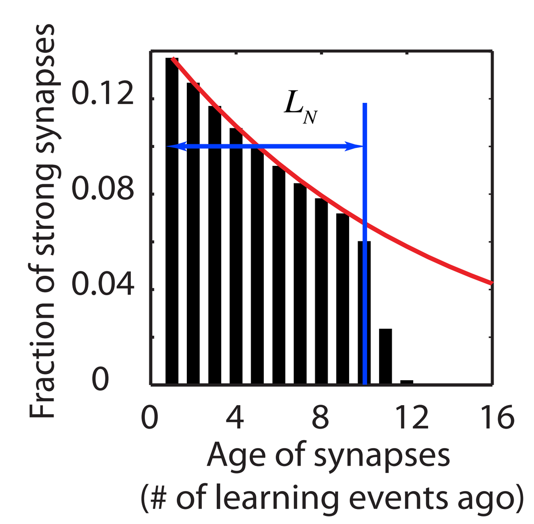


1. The dendrite is the unit of learning
2. Plasticity occurs when two learning threshold are crossed
3. Strengthened/refreshed synapses are protected up to a certain age

3. Main result: capacity is greatest for dendrites of "medium" length (containing a few hundred synapses)

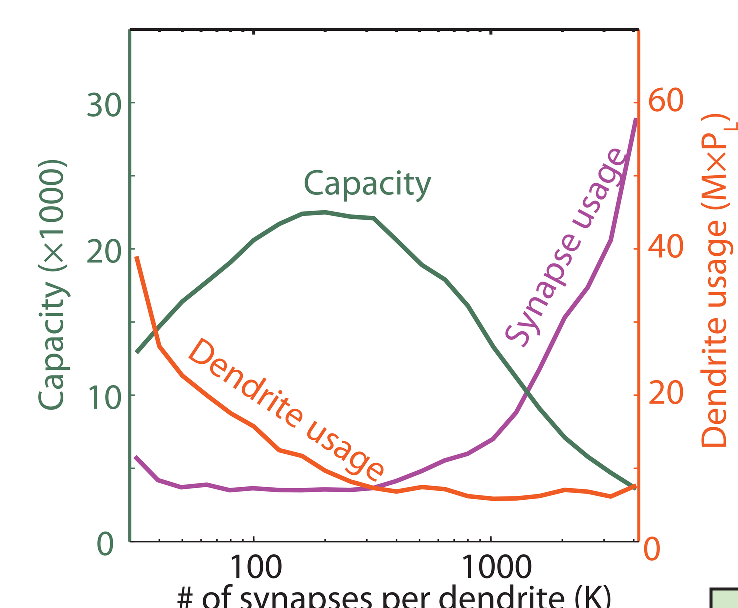


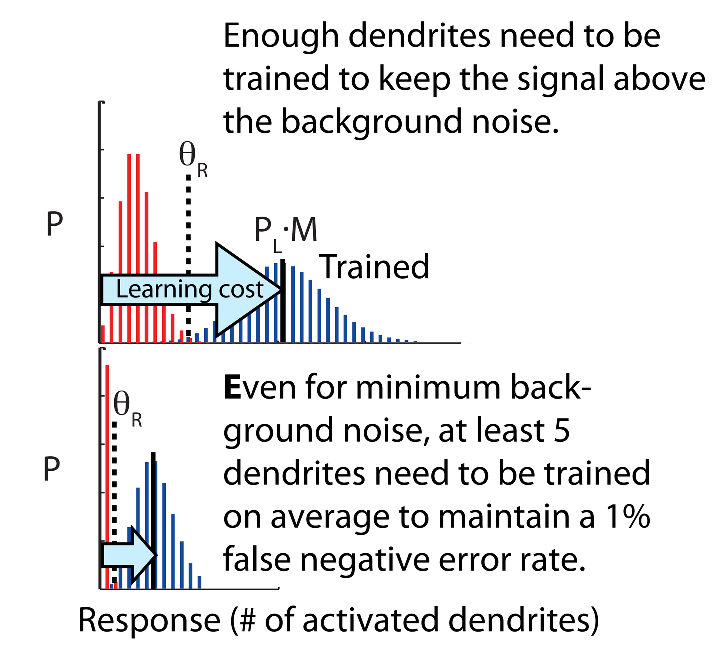




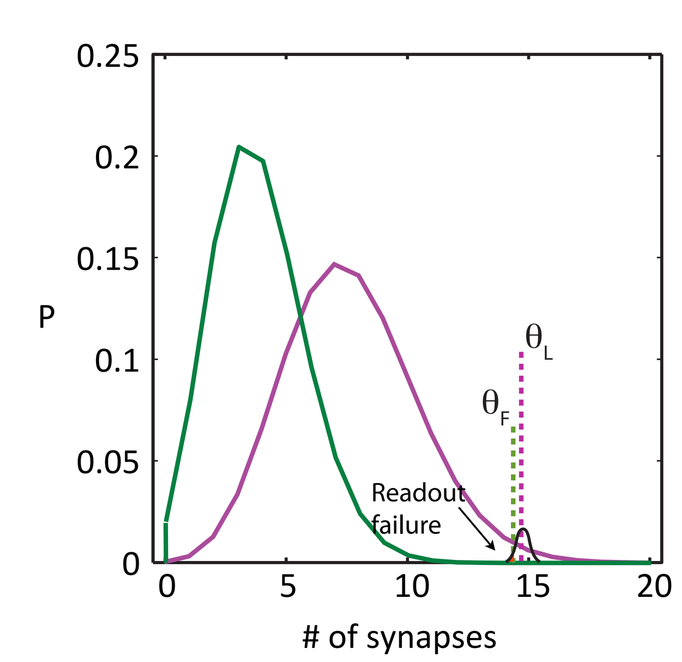
$$\text{Capacity} = L_N / P_L = \frac{\dfrac{-\log(2)}{\log(1-\theta_{Lpre}/K)} - 1}{P_L}$$

4. Why short and long dendrites are bad



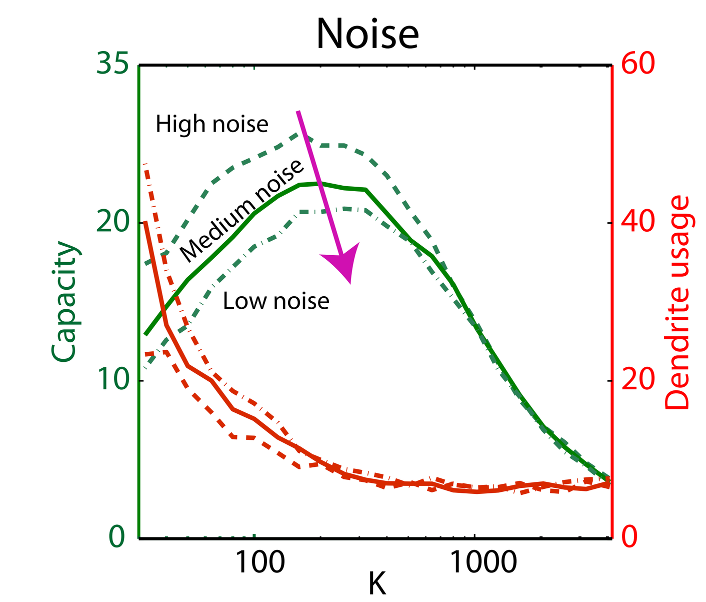


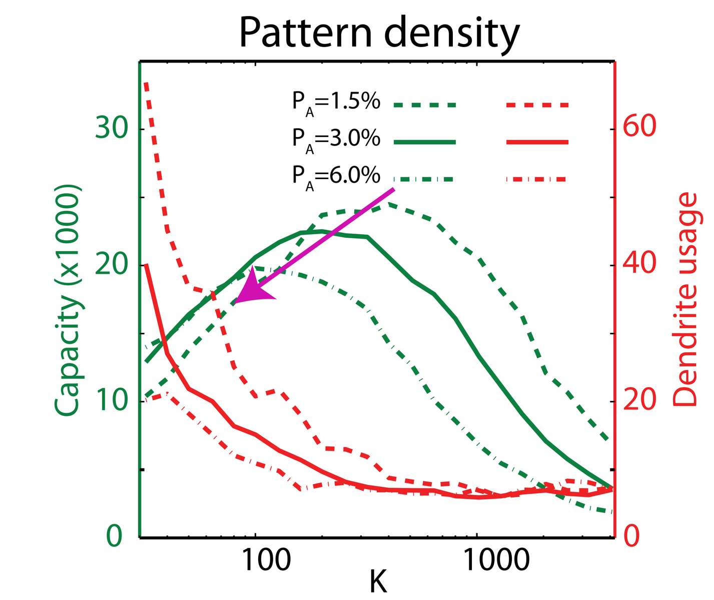
Long dendrites are more expensive to train than short dendrites (per dendrite), and thus lower capacity once the minimum number of subunits (e.g. 5) is being trained.

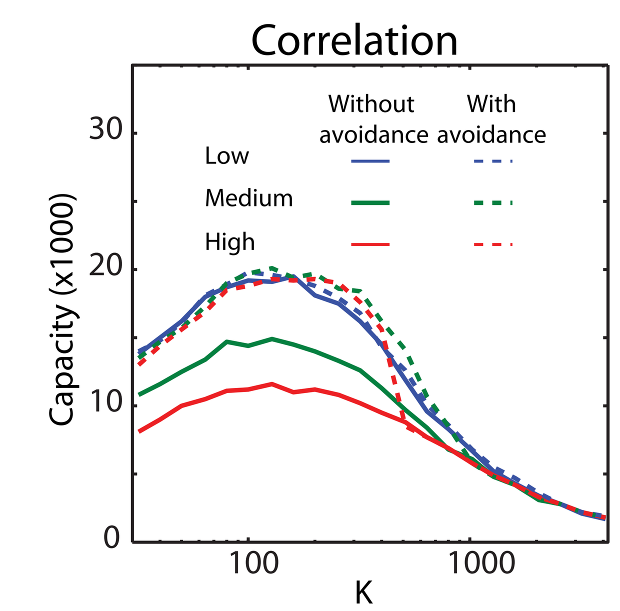


Short dendrites suffer from:
1. greater susceptibility to noise
2. more readout failures
3. dendrite availability

5. Effect of noise, sparseness, and correlation







In cases of correlated inputs, capacity is substantially reduced by variability caused by redundant copies of the same RF providing input to a given dendrite. A mechanism that discourages redundant input to a dendrite can therefore substantially boost capacity.

6. Conclusions

We show that capacity is maximized when dendrites are of "medium" length, that is, when each dendrite contains a few hundred synapses rather than 10's or 1000's of synapses. In particular, we show why both short and long dendrites suffer from severe capacity costs: long dendrites lead to wasteful over-representation, while short dendrites suffer from (1) greater susceptibility to noise, (2) more readout failures, and (3) a previously unreported problem of "dendrite availability". We also studied the relationship between optimal dendrite size and (1) pattern density, i.e. the fraction of activated axons, (2) input noise level, i.e. the variability in burst strength across axons across trials, and (3) the degree of correlation between axons, i.e. the number of input axons that have overlapping receptive fields and tend to fire together. We found that noise pushes the optimal dendritic morphology towards longer dendrites, whereas increased density push the optimum towards short dendrites. Funded by an NSF CRCNS grant (IIS-0613583).

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