Synaptic Pruning in Development: A Novel Account in Neural Terms

Gal Chechik Isaac Meilijson and Eytan Ruppin *
Schools of Medicine and Mathematical Sciences
Tel-Aviv University Tel Aviv 69978, Israel
gal@devil.tau.ac.il ruppin@math.tau.ac.il
Correspondence should be addresses to Eytan Ruppin

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A fundamental phenomenon in brain development is the reduction in the amount of synapses which occurs between early childhood and puberty. Recent studies in humans show that synaptic density grows steadily until the age of 2 years, remains constant for few years, and then decreases continuously until puberty [1, 2]. The plateau level in early childhood is up to 60 percent higher than adult levels, as observed also in primate studies [3, 4]. While the data is clear, the reason for this course of development is not: what advantages could such a seemingly wasteful developmental strategy offer? Some researchers have hypothesized that synaptic elimination can reduce the interference between memories, thus yielding better performance [5]. This paper shows that in the general modeling framework of associative memory networks this explanation does not hold. We put forward a different explanation: the observed profile of synaptic density changes arises due to the existence of metabolic energy constraints. Efficient memory storage in the brain then requires a specific learning process characterized by initial synaptic over-growth, followed by judicious synaptic pruning.

Our approach is motivated by the strong correlation observed between synaptic density and energy consumption in the brain (which is a major consumer of metabolic energy) [6]. Synaptic density is hence a very costly resource which should be optimized during development. By analyzing the network's performance under various constraints such as limited number of synapses and limited total synaptic strength, we show that proper synaptic deletion can improve performance of networks with limited resources. The proof is based on signal-to-noise analysis of the neurons' input fields, and is applied to both the canonical Hopfield model [7], and the more biologically plausible low-activity model described in [8]. Our results are described below, omitting the derivations.

First, we find that if the synaptic weights w_{ij} are created in a Hebbian manner, there is no synaptic modification function $g(w_{ij})$ which can improve the network's performance. This result remains true even if memories are embedded in an initially noisy synaptic matrix and extends previous results of [9] on the Hopfield model. Consequently, synaptic deletion

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(which is just a special case of a modification function) cannot enhance performance, in contrast with the previouse suggestions.

What then is the role of synaptic pruning ? Given the restricted amount of synapses (limited by energy constraints) in the adult, we prove that the optimal synaptic modification strategy is **minimal-value deletion**, *i.e.*, delete all synapses whose values are below some threshold and leave all other synapses unchanged. This simple strategy uses local information only (hence is biologically feasible in principle) and requires a process of synaptic over-growth followed by deletion. Figure 1 demonstrates the superiority of minimal-value deletion over random deletion (equivalent to a connectivity matrix pre-defined before learning) and over the "clipping" strategy previously investigated by [9].

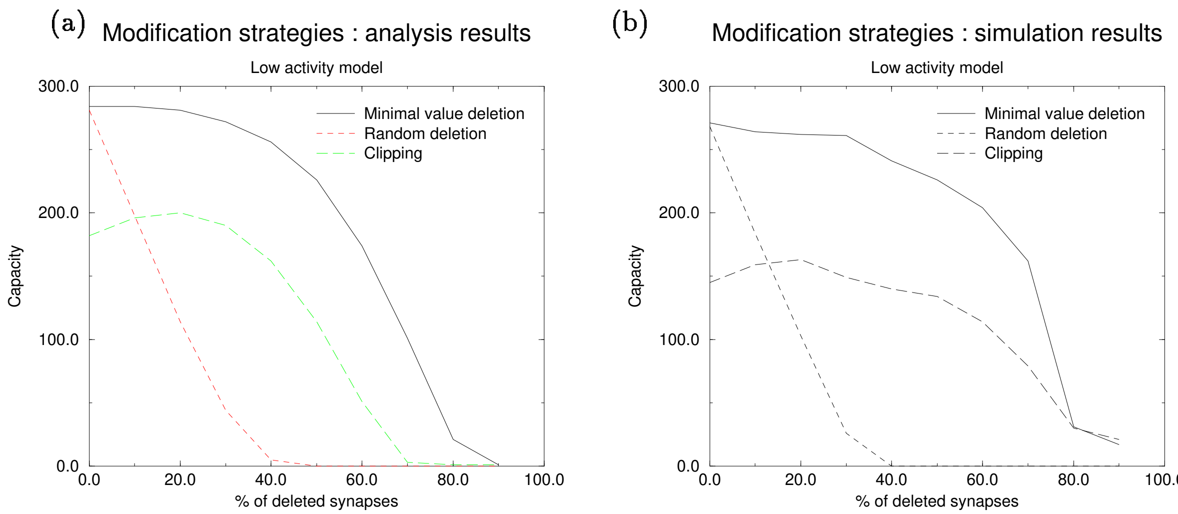

Figure 1: Capacity of a network with different synaptic modification strategies as a function of the synaptic deletion level. The capacity is measured as the maximal number of memories which can be stored in the network, and retrieved almost correctly in one step. (a) Analytical results (b) Simulation results. Network size is $N = 800$, and activity level is $p = 0.1$. Qualitatively similar results are obtained if capacity is measured after 10 iterations.

Assuming minimal-value synaptic deletion, what is the sparseness level that maximizes capacity ? We studied the performance of networks having a fixed number of synapses but with different sizes (*i.e.*, a larger network has sparser connectivity). As shown in Figure 2, maximal performance is achieved at deletion of about $60\% - 70\%$, similar to the levels observed during development.

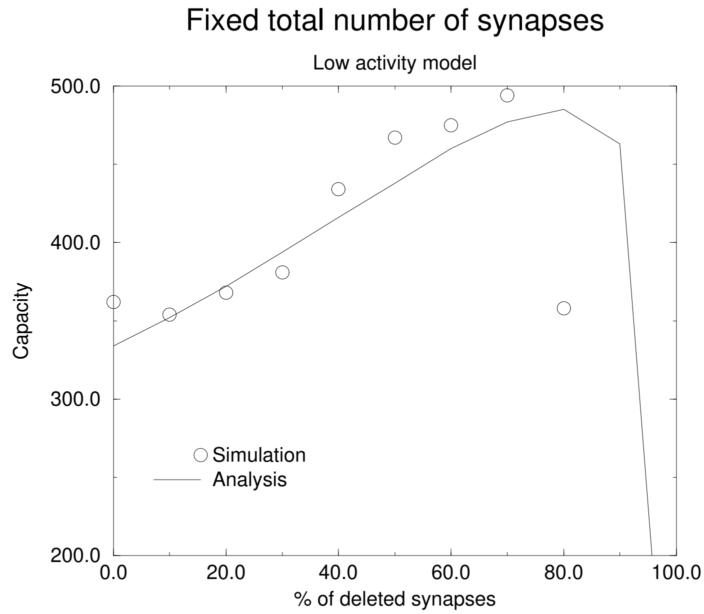

Figure 2: Performance of different networks with same synaptic resources as a function of the network connectivity. All networks have identical total number of synapses, but different sizes and connectivity. Capacity at the optimal deletion range is 45% higher than in fully connected networks.

Beyond the theoretical interest, minimal-value deletion can be realized in a biological manner. There are two possible realizations: a mechanism that operates on the individual synaptic level and 'kills' weak synapses, or a neural-level mechanism. We show that the action of neurally-based synaptic maintenance mechanisms [10] that regulate normal synaptic turnover may realize a near optimal strategy in which most synapses below some threshold vanish while the others assume some common value. In optimally sparse networks (figure 2) it is fairly similar to minimal-value deletion.

Implementing minimal-value deletion suggests interesting cognitive predictions: Figure 3 traces the network's performance during continuous memory storage of new patterns accompanied by changes in synaptic density that roughly mimic those taking place during human development. As evident, remote memories are better retrieved than recent memories (compare retrieval of memory stored at 5 and 15 years of age). This counter intuitive result corresponds to the inverse retrieval gradient found experimentally [11]. The model presents the first neural account of the intriguing phenomenon of childhood amnesia, replicating the well known sharp demise of memory in early childhood.

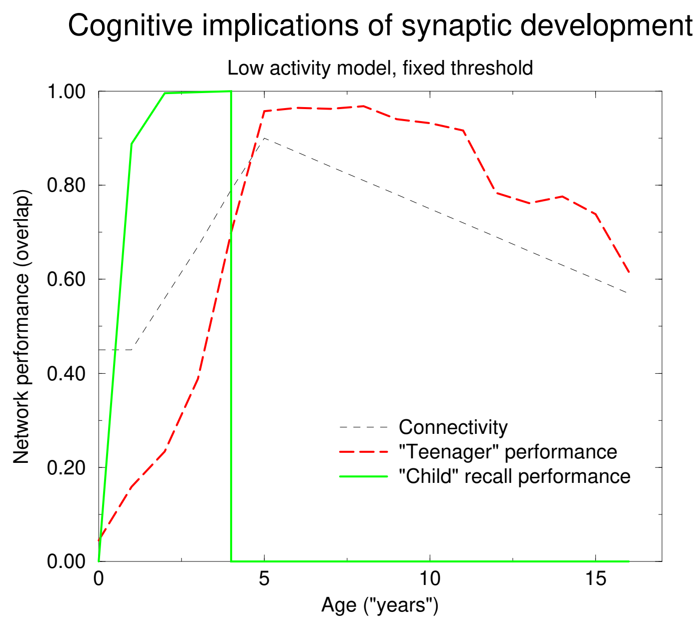

Figure 3: Performance of the network as a function of time. Performance is tested both in an early ("infant") stage, when network connectivity has reached its peak, and in a later phase ("teenage") after more memories have been embedded in the net. At each time step ("year") m memories are taught, and networks connectivity is changed following human data. the older 'teenager' network fails to recall infant memories. Network parameters are $N = 300$, $m = 4$.

In conclusion, this study involves an analysis of optimal synaptic modification strategies in a broad class of associative memory networks. Our results provide novel and important insights to understanding the massive synaptic pruning in infancy, and its relation to childhood amnesia.

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