Neuronal and Synaptic Packing Densities

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From the anatomical point of view, synapses in the central nervous system can be conveniently classified according to the detailed morphology of the synaptic profiles in electron-microscopic images into one of two classes, *Gray type I* and *Gray type II* synapses (Gray, 1959). Using a combination of electrophysiological, pharmacological and anatomical criteria, type I synapses, also known as *asymmetrical synapses*, have been found to be excitatory, while type II synapses, also known as *symmetrical synapses*, act in an inhibitory manner (Douglas and Martin, 1990).

Synapses are small. The area of contact between the pre- and the postsynaptic process has a diameter of 0.5-2.0 μm, while the presynaptic terminal is only slightly larger. This implies very high synaptic packing densities. For instance, in cat visual cortex, one cubic millimeter of gray matter contains approximately 50,000 neurons, each of which carries on average 6,000 synapses, giving a grand total of $3 \cdot 10^8$ synapses per mm^3 (Beaulieu and Colonnier, 1983, 1985). It has been estimated that about 84% of these are excitatory synapses, and 16% are inhibitory synapses.

In the mouse cortex, neurons and synapses are closer packed: about $92,000$ neurons and $7.2 \cdot 10^8$ synapses per cubic millimeter (Braitenberg and Schüz, 1991). Thus, mouse cortex can be thought of as a regular, crystalline-like three-dimensional lattice, with a synapse every 1.1 μm! Braitenberg and Schüz (1991) estimate the extent of neuronal processes in a 1 mm cube of cortical tissue, coming up with the staggering amount of 4.1 km total length of axonal processes (at an average diameter of 0.3 μm) and 456 m total length of dendrites (at an average diameter of 0.9 μm) in this volume. In other words, the "average" nerve cell in the mouse cortex receives input from 7,800 synapses along its 4 mm of dendrites and is connected with 4 cm of "axonal wire" to other cells. Note that these are values obtained by averaging over all cell types in cortex; neurons from different cell classes, such as basket versus pyramidal cells, have quite different values.

Given a cortical density of 100,000 cells per mm^3 in primate cortex, a synaptic density of $6 \cdot 10^8$ per mm^3, a total surface area of about 100,000 mm^2 for one cortical hemisphere and an average cortical thickness of about 2 mm, the average human cortex contains on the order of 40 billion neurons and 240 trillion synapses ($2.4 \cdot 10^{14}$), quite impressive numbers given the current count of about 10^{11} transistors in the memory and central processing units (CPUs) of a modern parallel supercomputer.[1]

References

[1] Of course, the connectivity among the components in the CPU is three to four orders of magnitude lower than the connectivity of a cortical cell. On the other hand, the cycle time of such machines, in the $5-30$ *nsec* range, compares very favorable against neuronal time-constants in the $5-30$ *msec* range.

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