Speed Limits in Mammalian Brains: Scaling Constraints from Biophysics

Speed limits in mammalian brains: scaling constraints from biophysics

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Optical physiology and synaptic learning rules:
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Brain scaling and evolution:
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Fig. 15. Brain-body relations in 623 living vertebrate species enclosed in minimum convex polygons. The samples are 309 mammals, 180 birds, 46 bony fish, 40 amphibians, and 44 reptiles. Additional data are: M, Tursiops truncatus (bottle nose dolphin); a, elephant; b, humans; c, Orcinus orca (killer whale), two dinosaurs (l, Tyrannosaurus; k, Brachiosaurus); g, the 150-million year old mammal, Thrinodon, and e, the early bird, Archaeopteryx. (From Jerison, 1987, reprinted by permission)
Inferring general functional principles with comparative anatomy
We would now like to compare neurons not just from similar animals, but from animals throughout the zoological series, and more particularly from vertebrates. In doing so, we shall carefully limit comparisons to homologous cells in corresponding neural centers. The result of this exercise is rather surprising. From the appearance of the very first vertebrates, some individual neurons or groups of neurons have been modified more or less continuously before reaching their current state of refinement. In contrast, some neurons remain unchanged over long periods of time, seemingly impervious to all progress.

This suggests that the nervous system can be divided into two quite distinct systems by the differential action of evolution on large groups of constituent cells. One group, confined to the sensory nervous system, appears to have reached an endpoint in refinement, at least as far as the differentiation of its constituent neurons is concerned; it appears now to be susceptible only to increases in cell number or size. The other group, found mainly in the central nervous system—and more particularly in the cerebral cortex—has continued to evolve, and during the course of refinement has always matched the progression of the animal series, increasing both in size and refinement.

![Axons Diagram](image)
Functional advantages of axon size and type

- Compactness (35-70% of axons)
- Per-spike energy cost (30-65%)
- Extreme speed (0-5%)

Explaining scaling trends with biophysical principles

- Are white matter axons under selection pressure for speed?
  - Synaptic delays and action potentials: 1 msec
  - Synaptic potentials: 10-100 msec
  - Cross-brain conduction: 10-200 msec
- Can ultrastructural trends account for gross scaling trends?
  - Geometric “accounting”
The neocortex

**gray matter**
- external rind containing neuronal cell bodies and local connections

**white matter**
- closely packed axons making long-distance connections
Axons of the corpus callosum are well-packed.
Myelination becomes more prevalent in larger brains

Axon density decreases in larger brains
The largest axons increase in size with brain diameter

J.M. Ritchie (Hursh 1939)
2. Minimal cross-brain conduction time is ~2 milliseconds*

*(but the slowest times can be of order 1 second!)

Preservation of shortest cross-brain conduction times
Axon scaling in other pathways

- Corticospinal axons for fine movement
- V1 to MT projecting axons
- Optic nerve
- Cerebellar parallel fibers

Parallel fibers have small diameters even in large brains

K.D. Wyatt
A subpopulation of large parallel fibers in big brains

Metabolic limits may constrain white matter composition
Very large axons take over big brains

Allometry of neocortical white and gray matter

The expansion of neocortical white matter relative to neocortical gray matter. As the size of the neocortical gray matter increases, the size of the associated white matter grows disproportionally; a proportional relationship would follow the red line. The volumetric data was obtained from the work of Heinz Stephan and his colleagues. The analysis was performed by Andrea Hasenstaub and the author.

J.M. Allman (1999), *Evolving Brains*
A length minimization argument for white matter volume

Zhang and Sejnowski (2000) PNAS 97:5621

Length minimization alone cannot predict volume

\[ W = \sum_{i=1}^{n} aL_i = (na) \left( \frac{1}{n} \sum_{i=1}^{n} L_i \right). \]  

Zhang and Sejnowski (2000) PNAS 97:5621-5626
Giant axons drive white matter volume in big brains

Conclusions from looking at neocortical axons

1. White matter composition varies with brain size
2. The fastest cross-brain conduction times are 2-5 msec
3. Metabolic limits may constrain white matter composition
4. Very large axons take over big brains
Spindle cells: a source of large axons?

Neuron density is smaller in large brains

Fig. 1. Neuron density in the cerebral cortex of various adult mammals is related to average total brain weight (Log-Log).

Neuron density is smaller in large brains

Density \sim V^{-1/3}
Links among scaling relationships in the neocortex

Journal of Neurocytology 31:289-298

Scaling relationships in the mammalian neocortex

Dr. Sam Wang, Princeton (KITP Brain Program 9/02/04)
Open Questions

- What functions require cross-brain conduction to be conserved?
- Who are the giant axons and what do they do?
- Why does neuronal density decrease with an orderly power law?
- What underlies other intracortical scaling relationships?
- What are other invariant quantities of neocortex?
- How do these principles apply to other systems?
The end
Allometry in the neocortex

H. J. Jerison (1987)

M. Hofman (1989)
What makes the brain folded?

- Development
- Cell biology
- Evolution and optimization
Beta-catenin overexpression induces mouse brains to fold

A. Chenn and C. Walsh (2002) Science

Normal brain  Pachygyric brain

In some cases, caused by cocaine use during pregnancy. Fewer neurons?