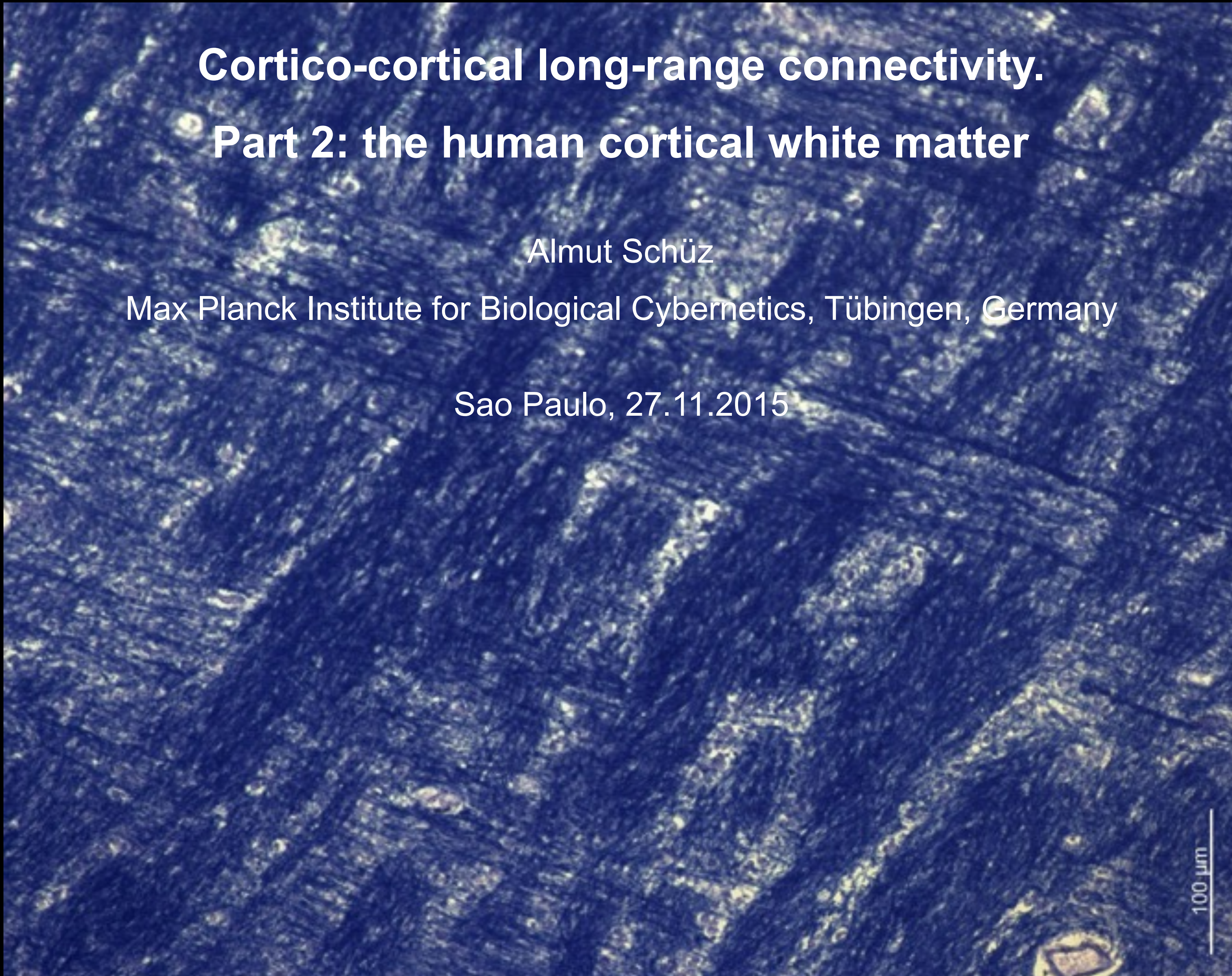
Cortico-cortical long-range connectivity.

Part 2: the human cortical white matter

Almut Schüz

Max Planck Institute for Biological Cybernetics, Tübingen, Germany

Sao Paulo, 27.11.2015

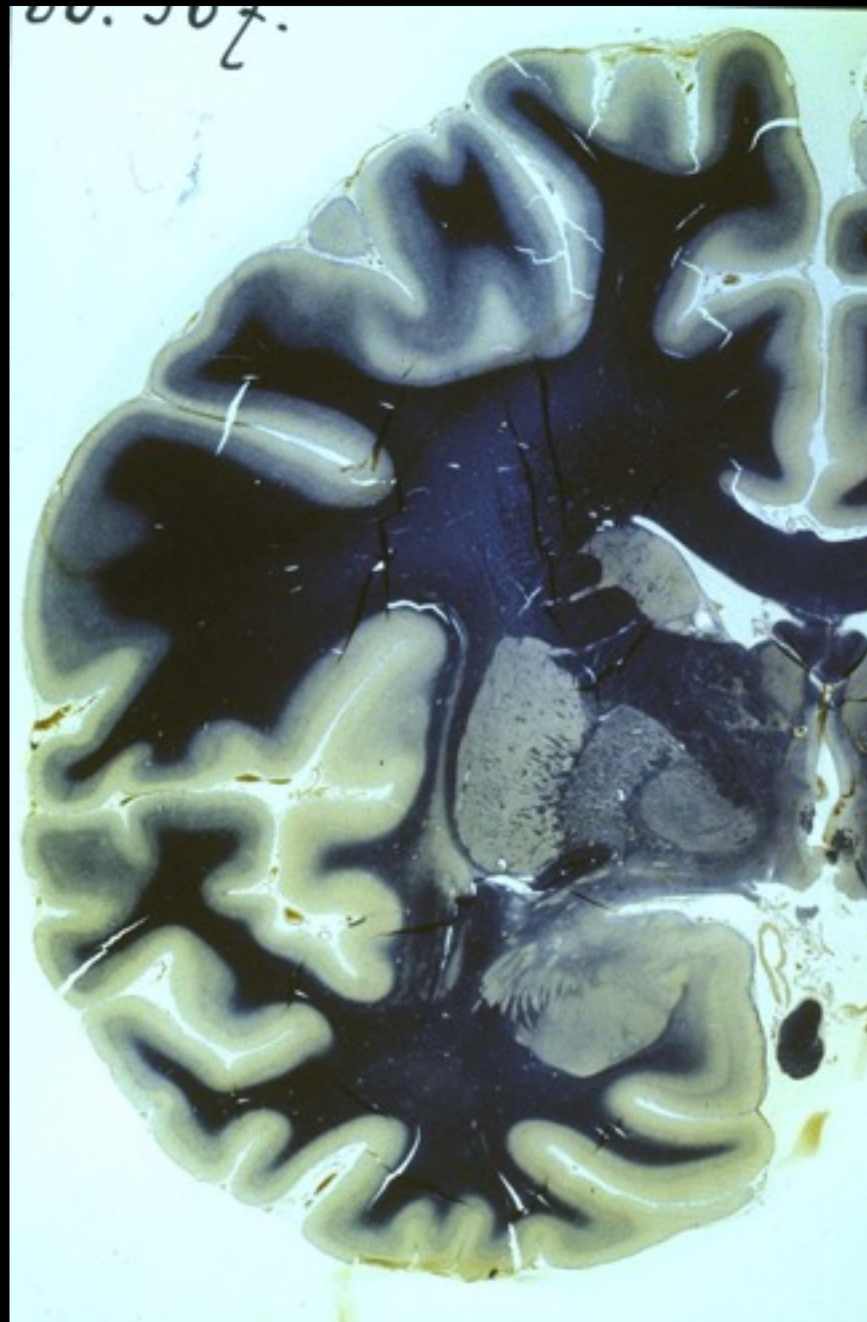


The human cortical white matter:

- Bundles of cortico-cortical axons in the white matter

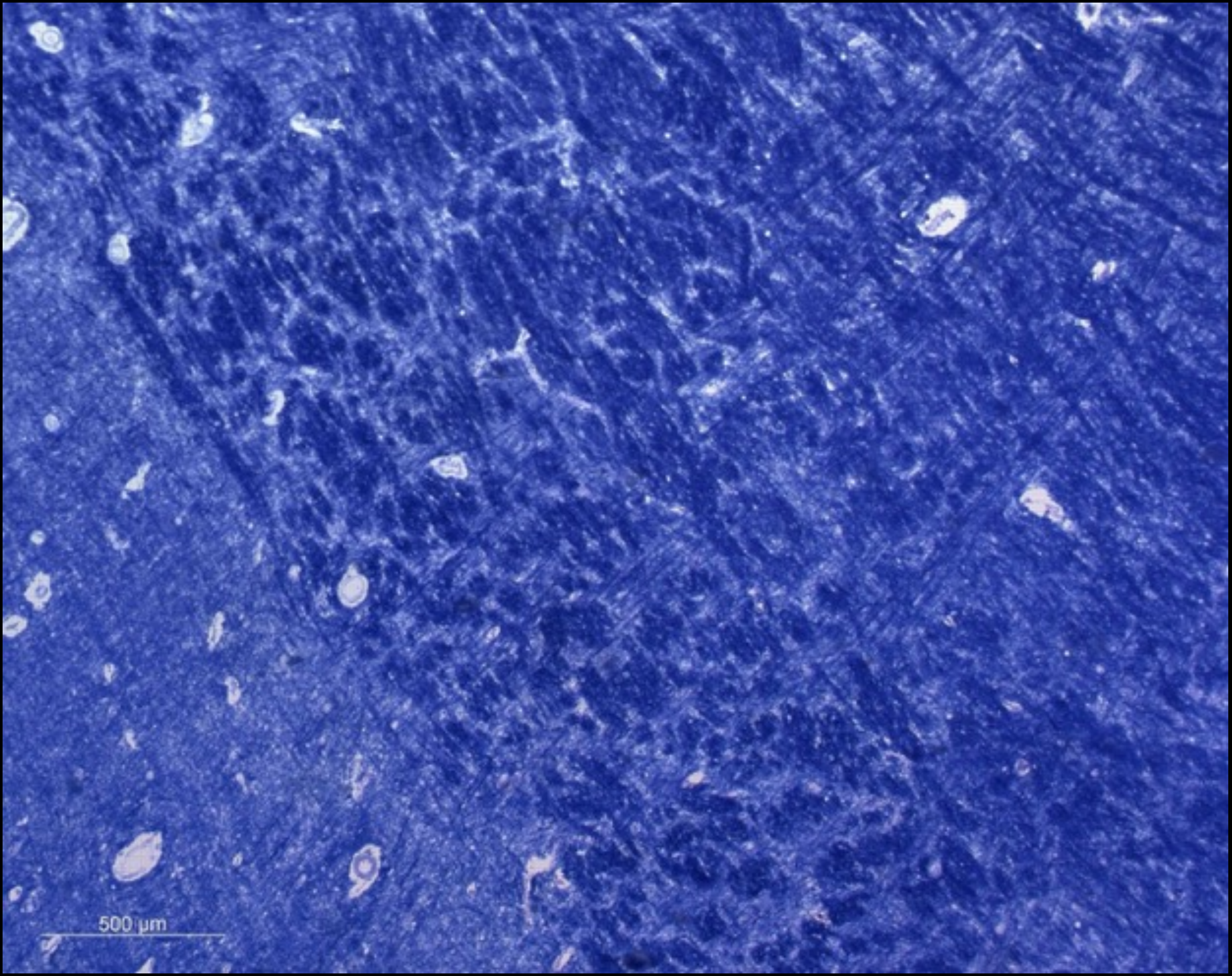
- Number of fibers (=axons)

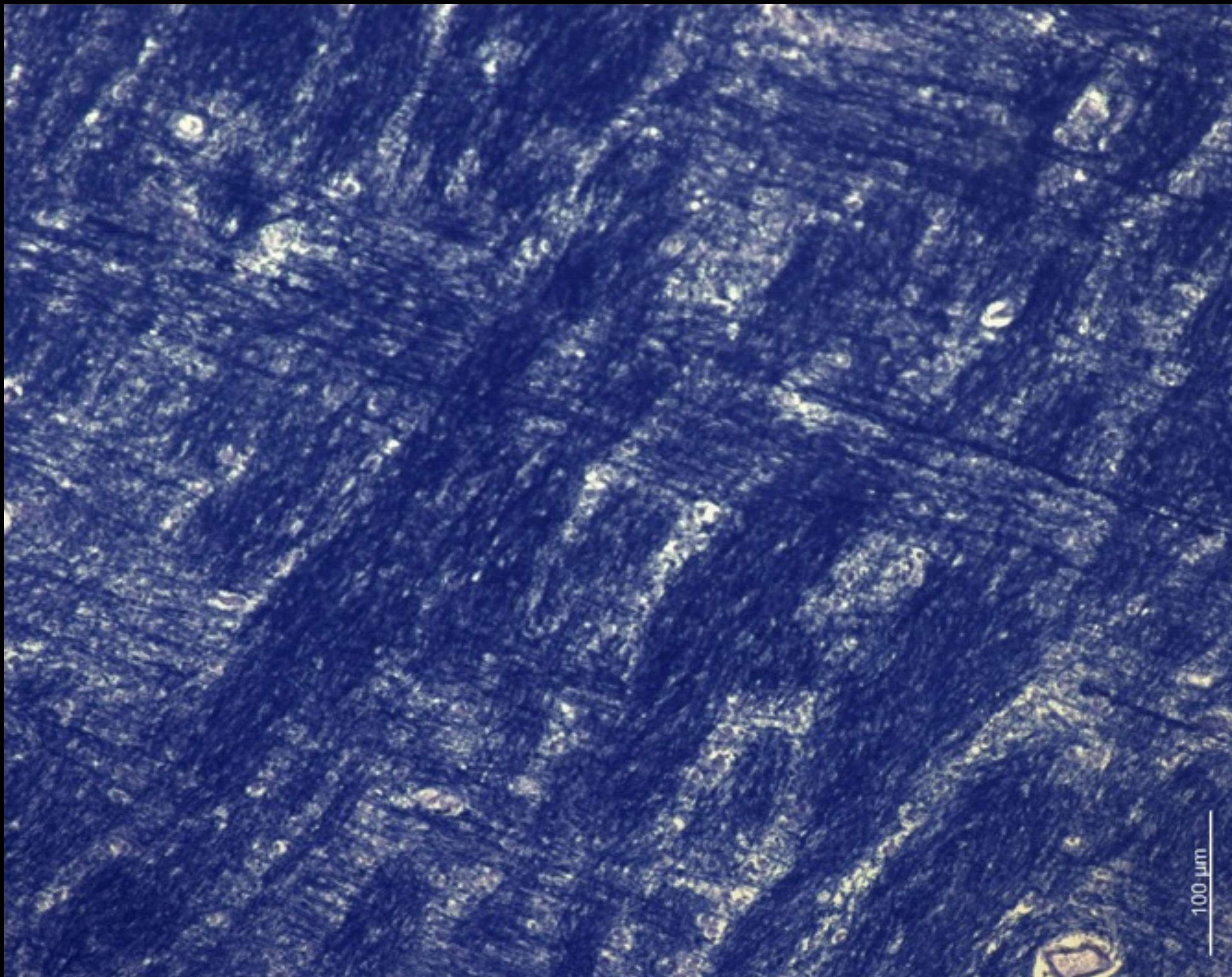
- Axondiameters



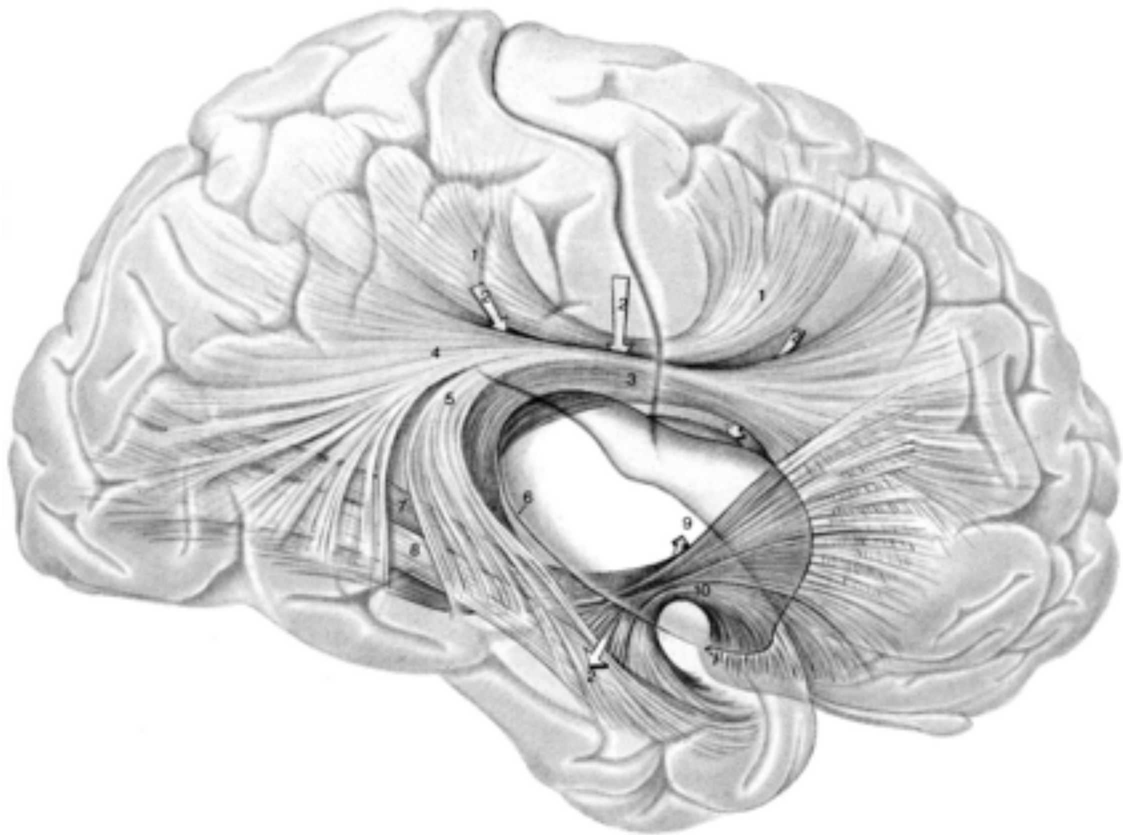
Section: Max Planck Institute for Brain Res. (Frankfurt)

Foto: Bernhard Hellwig (Tübingen)


500 µm


100 µm

3 superior longitudinal fascicle
1 superior occipitofrontal fascicle
8 inferior longitudinal fascicle
7/9 inferior occipitofrontal fascicle
10 uncinate fascicle



From: Nieuwenhuys, Voogd and van Huijzen (1980)

From Gluhbegovic and Williams (1980)

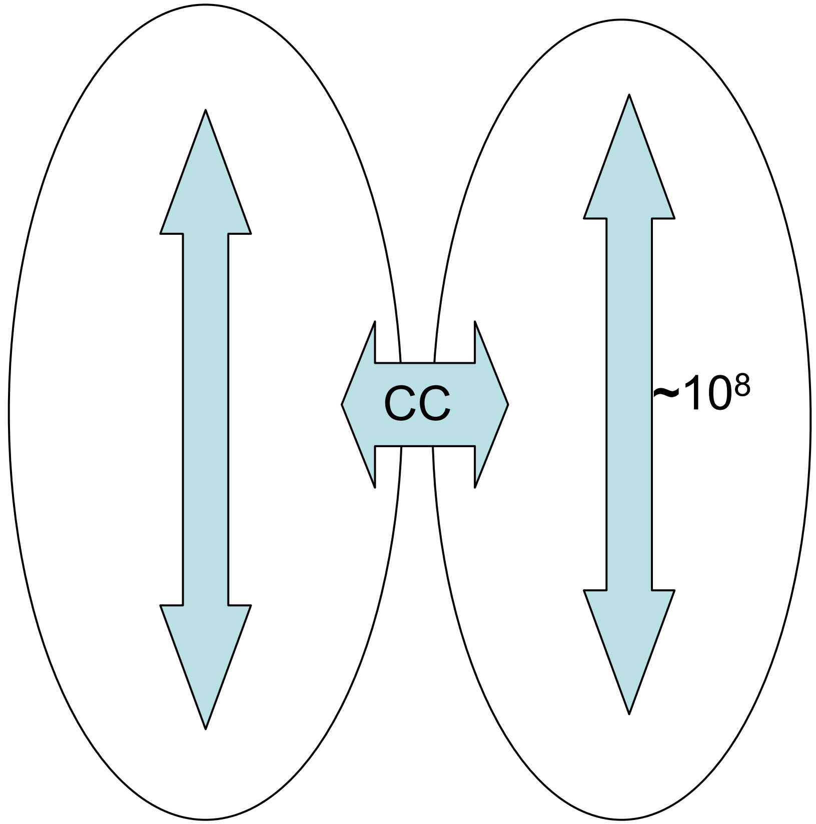
S superior longitudinal fascicle
▲ inferior longitudinal fascicle
△ uncinate fascicle and inf. occipitofrontal fascicle

Cross sectional area x density of axons

(338 000/mm^2 in the Corpus callosum; Aboitiz et al., 1992)

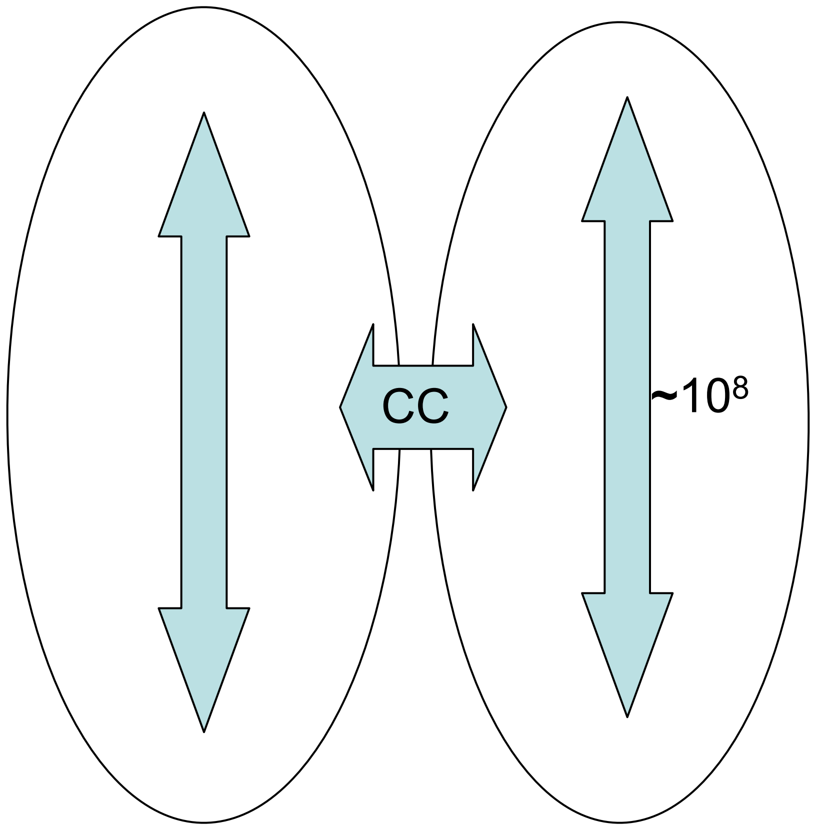
Number of fibres in the long-range fascicles of the white matter

Fascicle	cross-sectional area	number of fibres
Cingulum	19.6 mm^2	7.4×10^6
Sup. longitudinal Fascicle	114 mm^2	4.3×10^7
Uncinate fascicle + Inf. occipitofrontal fascicle	81 mm^2	3.1×10^7
Inf. longitudinal fascicle	19.6 mm^2	7.4×10^6
Sup. occipitofrontal Fascicle	16-32 mm^2	6×10^6 - 1.2×10^7
Total number of axons in the far-reaching fascicles of one hemisphere		*approx.* 10^8



2 – 3 x 10^{8} fibres in the corpus callosum
(Blinkov and Glezer, 1968, Aboitiz et al. 1992)

Number of long fibres
within one hemisphere
Comparable to that
Between hemispheres



2 – 3 x 10^8 fibres in the corpus callosum
(Blinkov and Glezer, 1968, Aboitiz et al. 1992)

However:

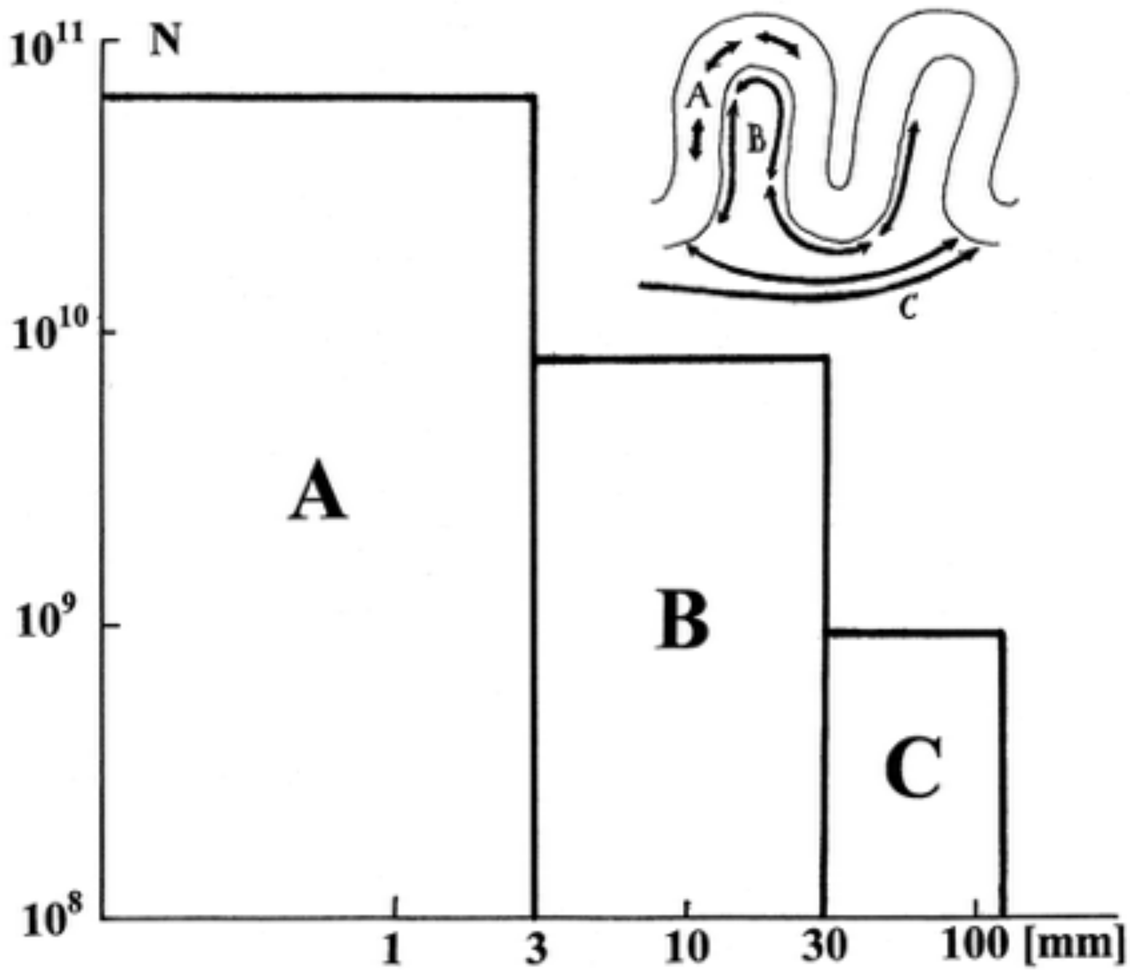
Total number of cortico-cortical fibres in 1 hemisphere
via the white matter: $\approx 6 \times 10^9$

i.e. only about 2 % ($\approx 10^8$) of those are in the long fascicles

Neurones in the cortex of 1 hemisphere	~ 7.5×10^9 (Haug, 1986)
~ 15% non-pyramidal cells	- 1.1×10^9 (Braak & Braak, 1986)
callosal neurones from 1 hemisphere	- 1 to 1.5×10^8
efferent neurones	- 2×10^8
Cortico-cortical ipsilateral neurones	= 6×10^9

only about 2% of those (10^8) are contained in the long fascicles

Length distribution of tangential fibres in grey and white matter:



From: Schüz and Braitenberg, 2002

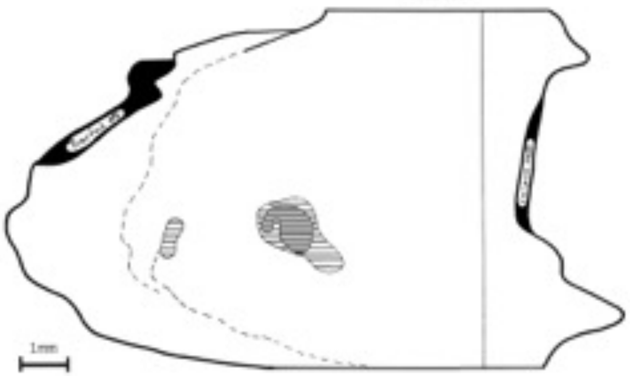
Conclusions on connectivity in the tangential plane

- Inverse relationship between number of fibres and fibre length

- The fibers in the long bundles are only a few percent of the total number of cortico-cortical fibres in the white matter.

- Closer regions have a higher probability of being connected than distant regions

Nr. 250898



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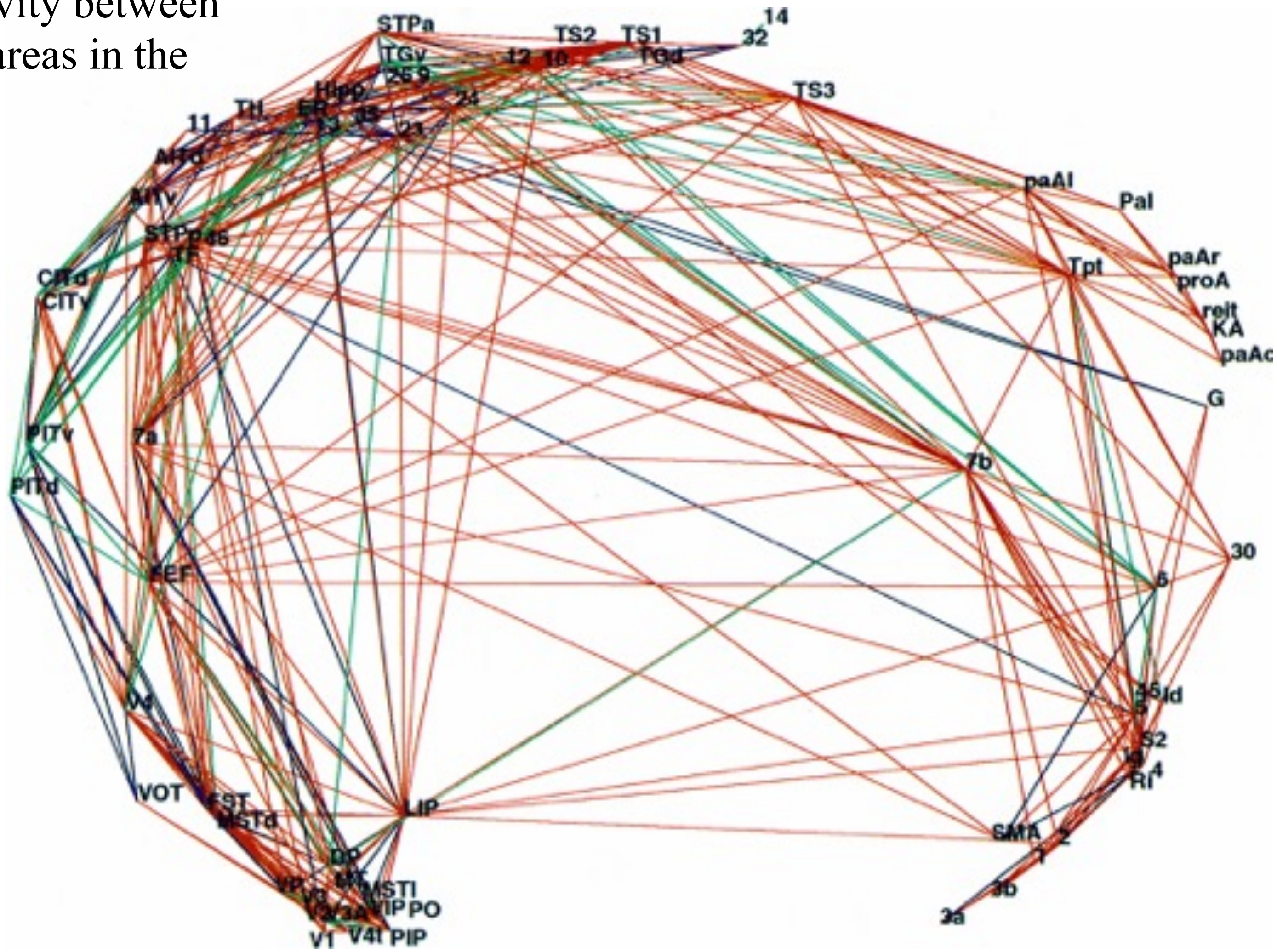
Connectivity between Cortical areas in the macaque



From: M.P. Young, Proc. R. Soc. Lond B (1993) 252, 13-18

Cat:

47.8% of connections between areas are „nearest-neighbour-or-next-door-but-one“ connections (Scannell et al., 1995)

Axon diameters in the long cortico-cortical bundles of the white matter

Together with Daniel Liewald

1) Conduction velocity in cortico-cortical axons ?

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Range in the nervous system 0.3 – 120 m/sec, i.e. x 400

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2) Dependence on brain size ?

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(frequency bands of LFPs, duration, temporal evolution, propagation of oscillations over the cortex, synchronization between distant regions)
(e.g. Buzsáki, Logothetis, Singer, 2013)

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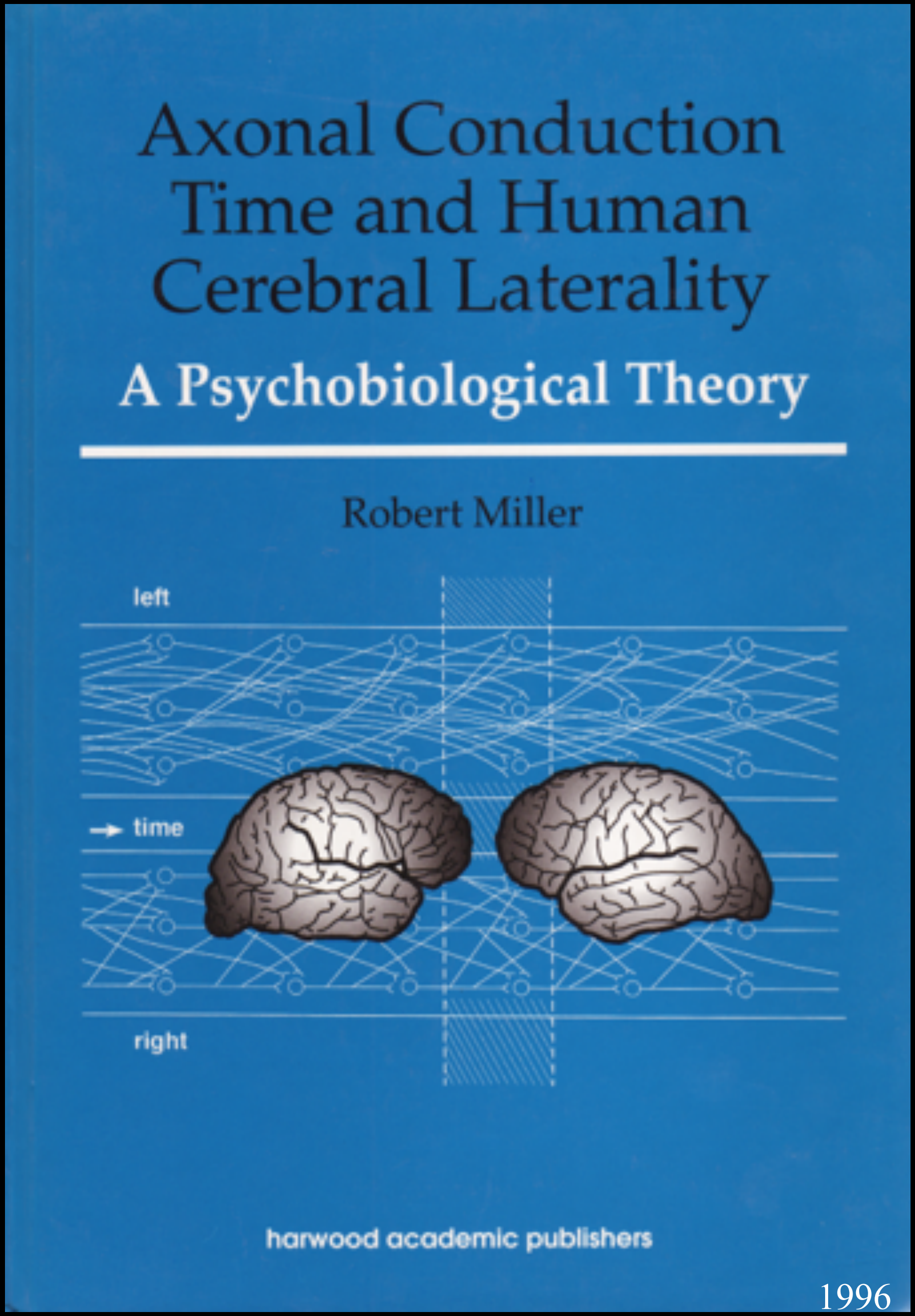
3) Providing data for comparison with data from diffusion weighted imaging

Differences between hemispheres?



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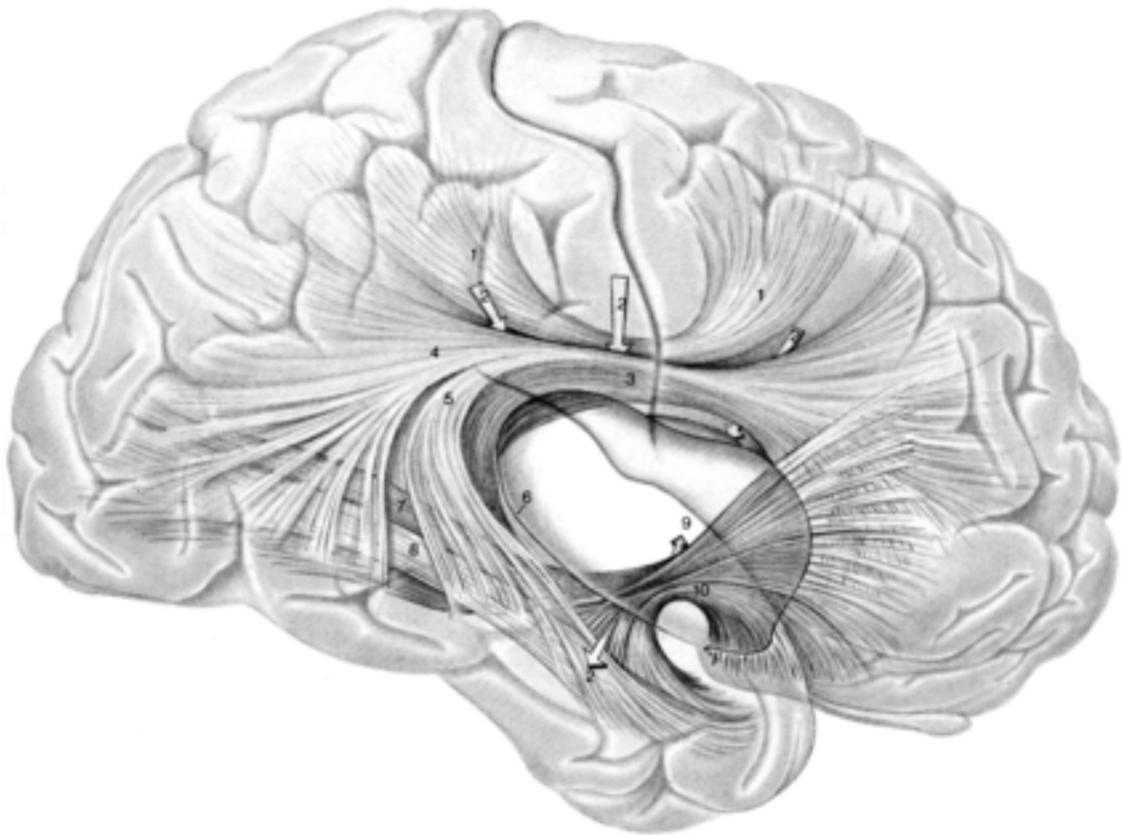
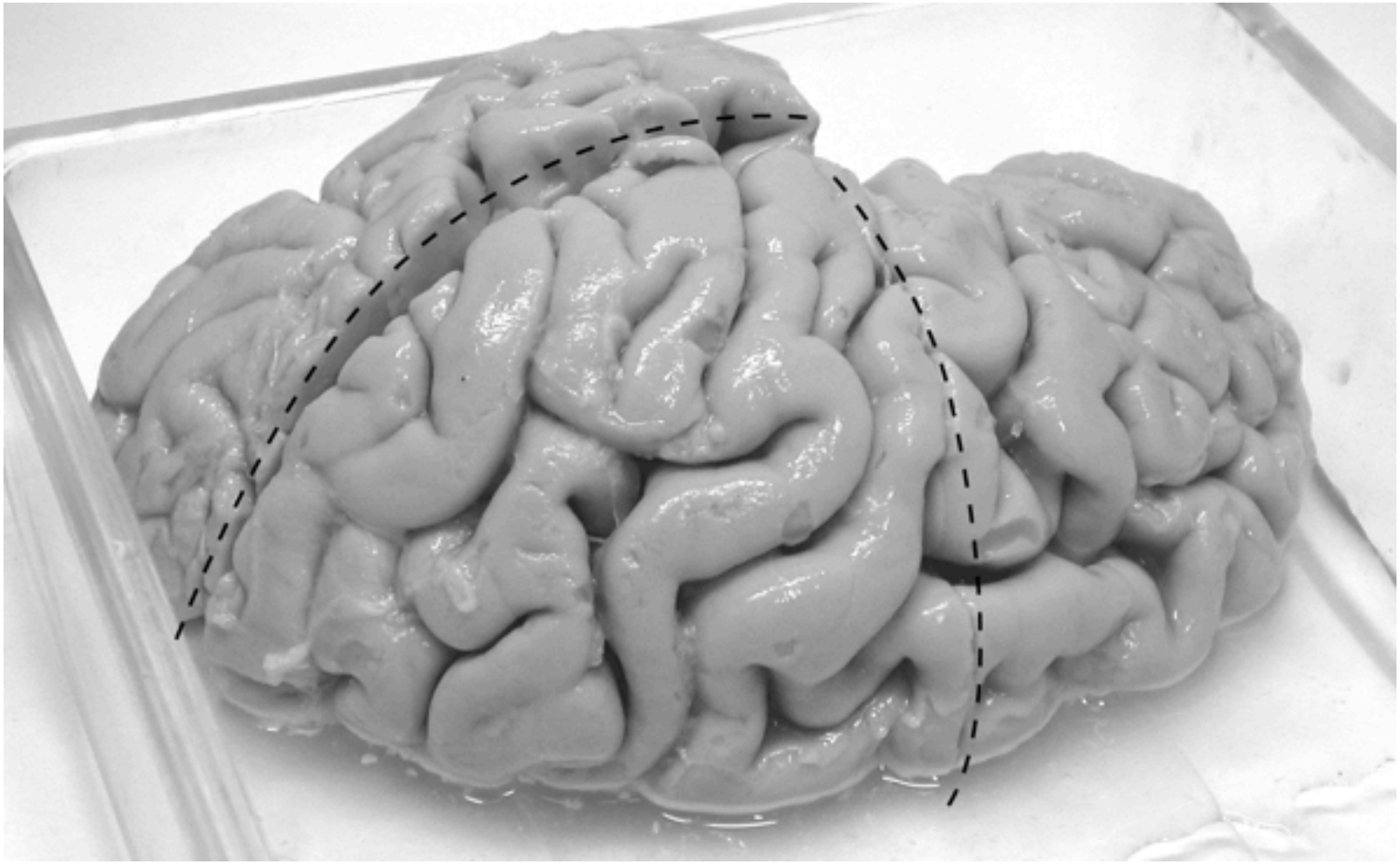
3) Providing data for comparison with data from diffusion weighted imaging

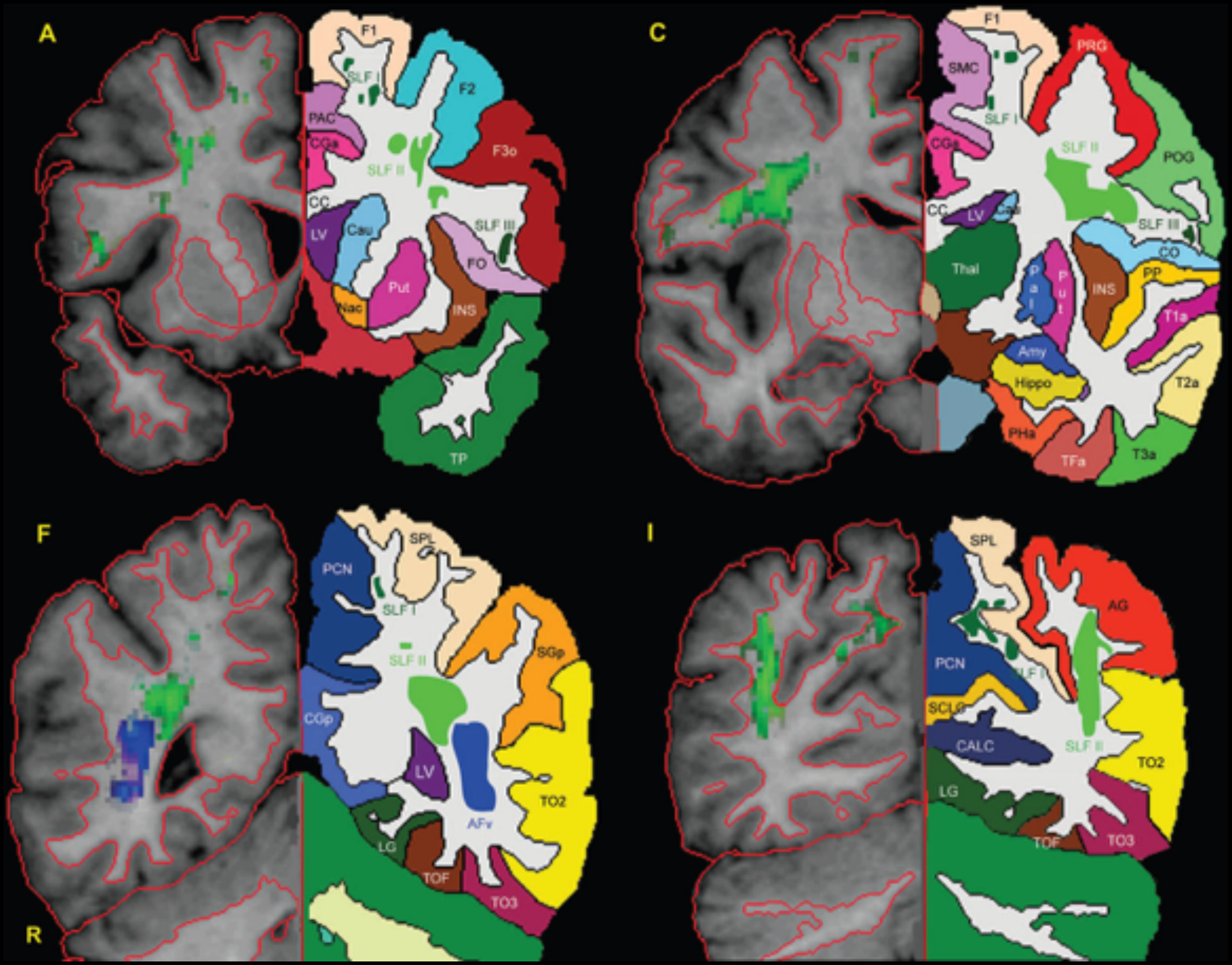
4) Differences in axonal diameter between hemispheres?



From: Nieuwenhuys, Voogd and van Huijzen (1980)

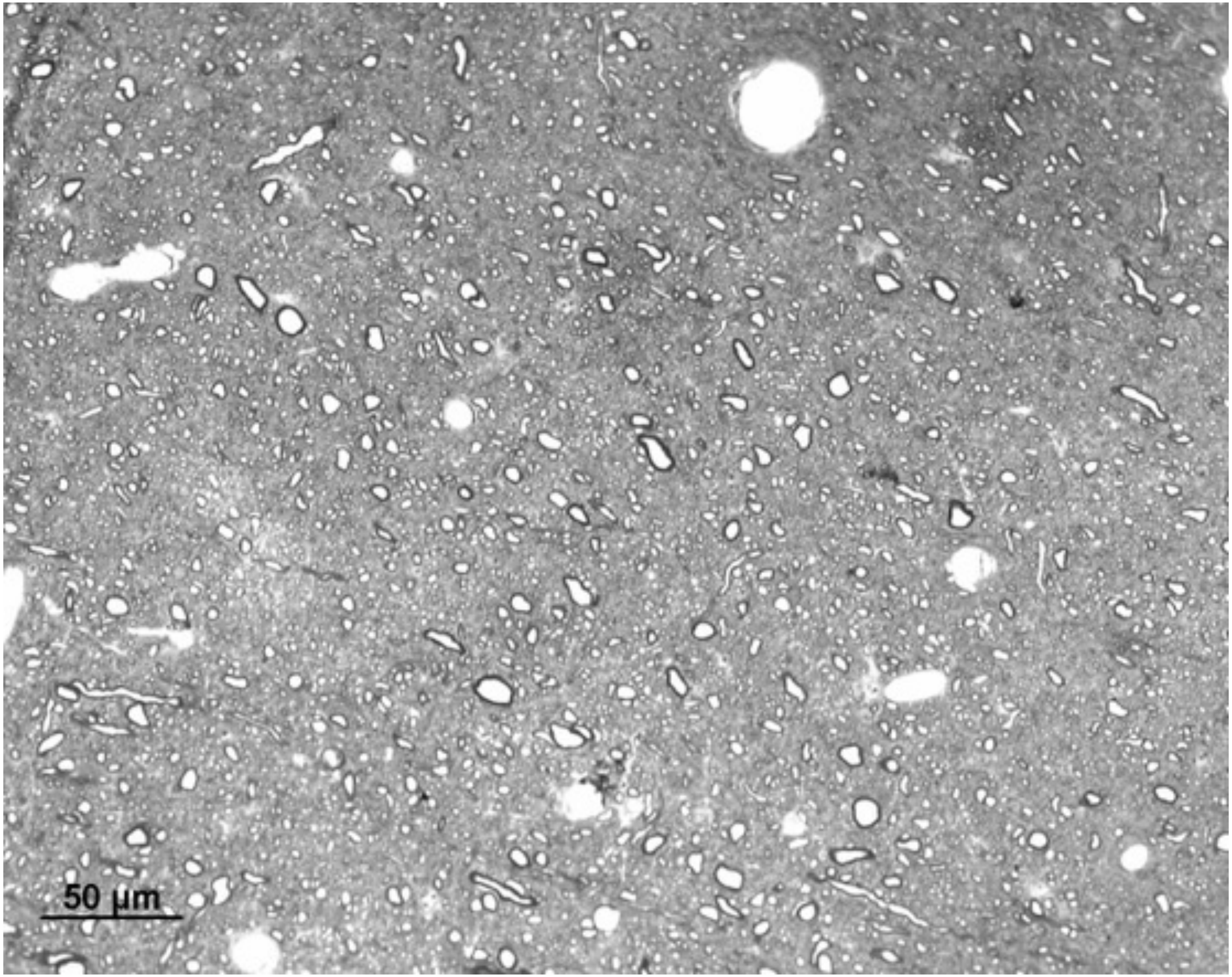


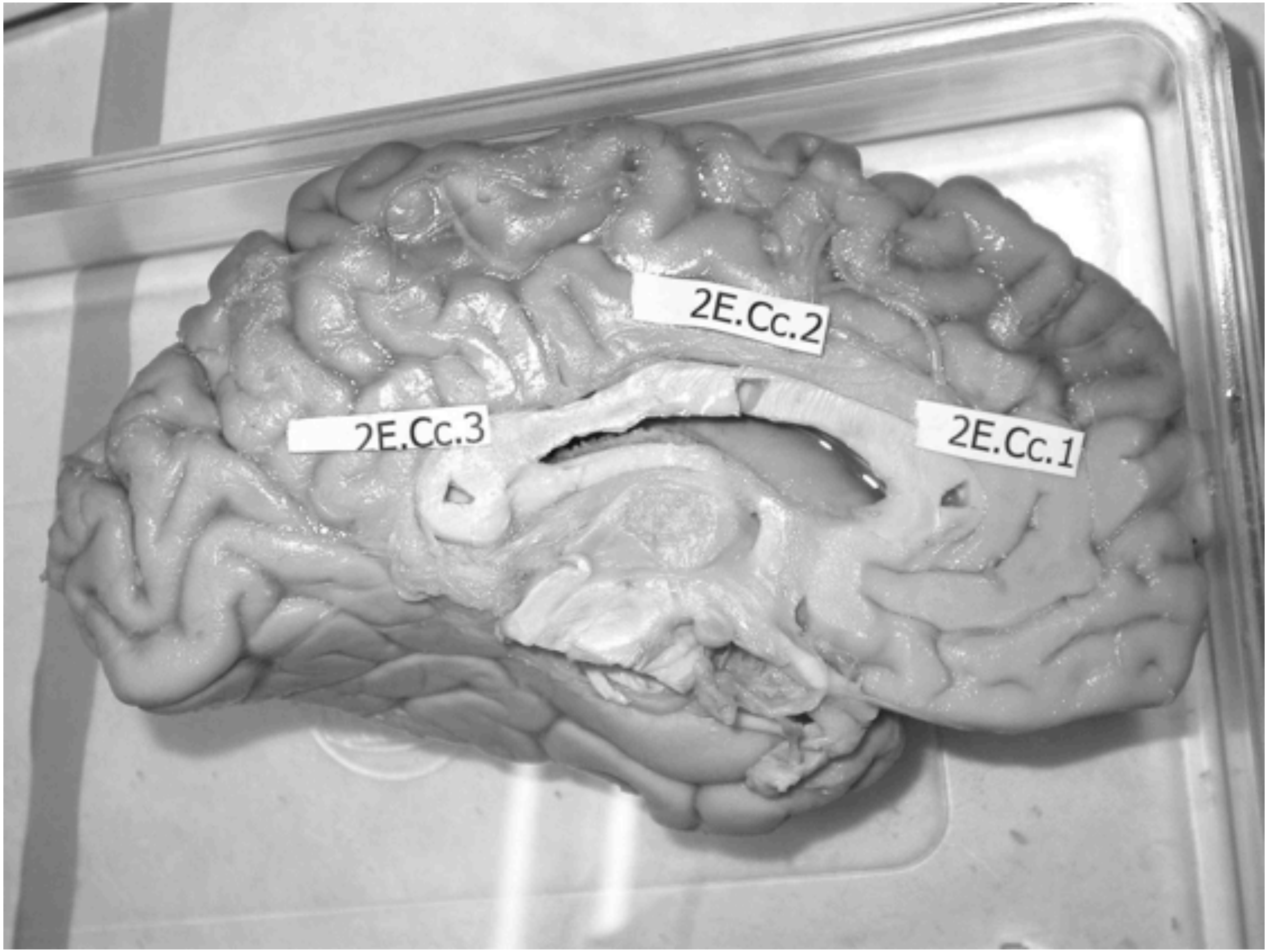

2E.FI.L

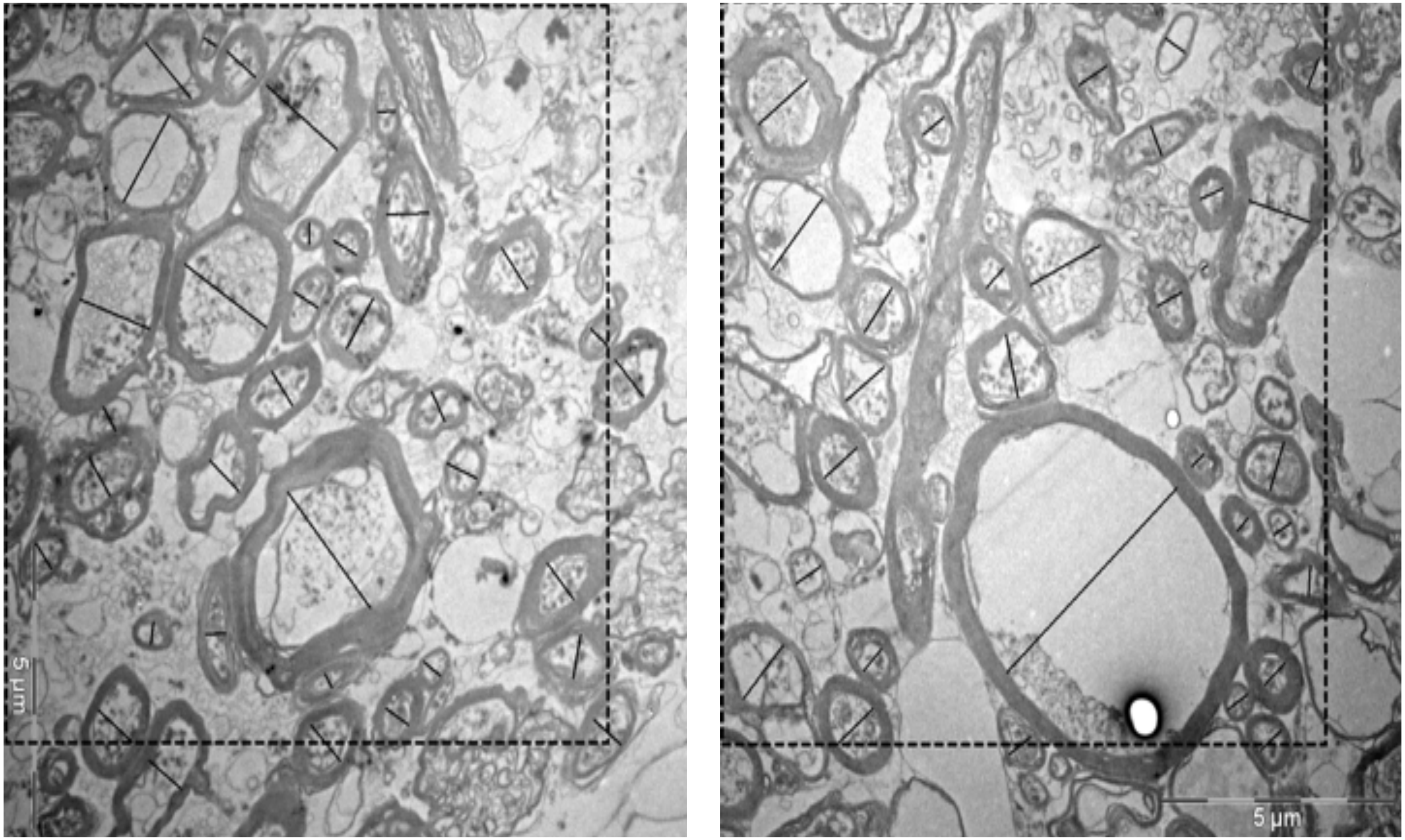


From: Makris, Kennedy, McInerney, Sorensen, Wang, Caviness Jr, Pandya, Cerebral Cortex 2005

Fasc. long.
monkey

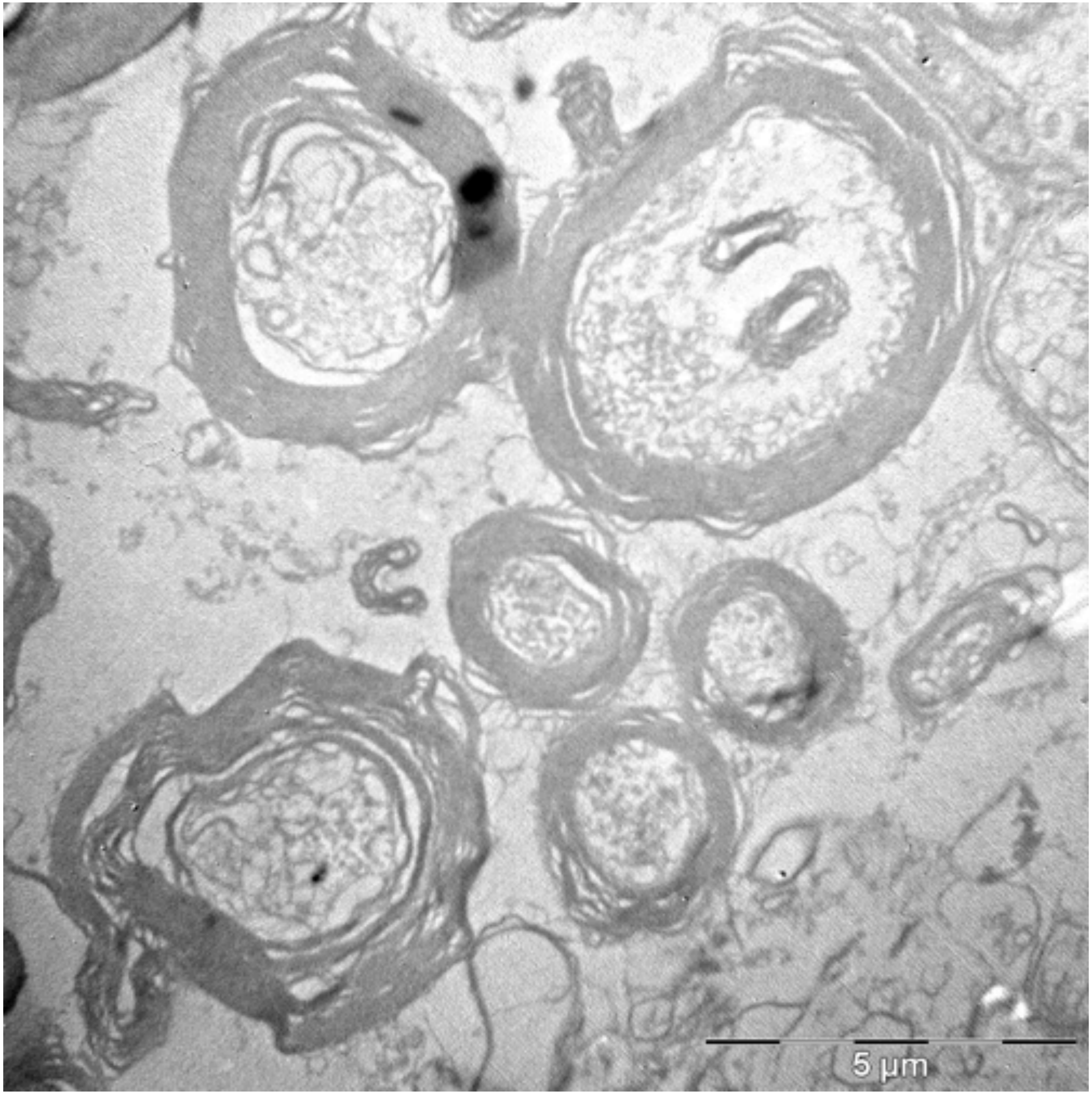



2E.Cc.2
2E.Cc.3
2E.Cc.1

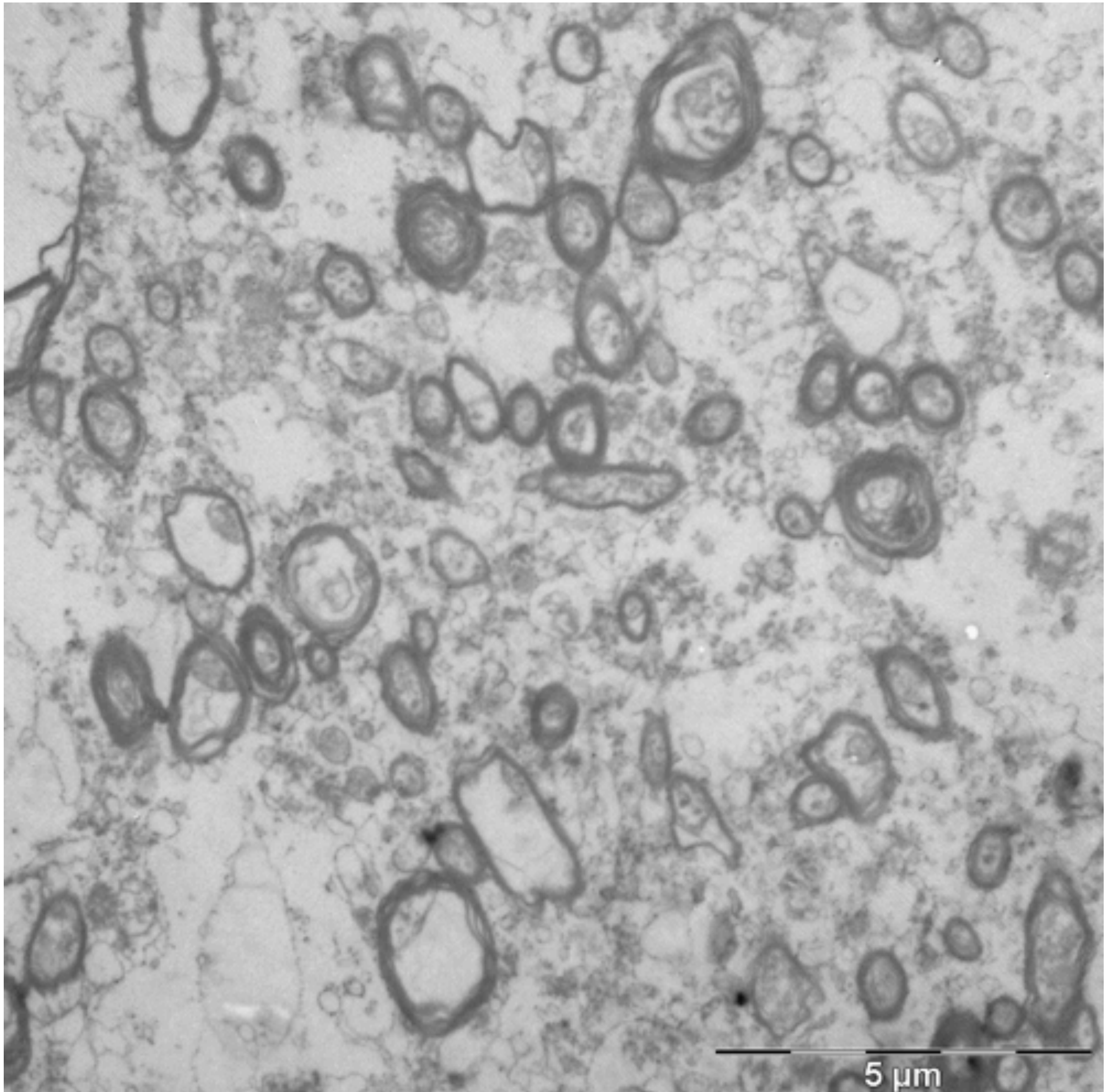


Human superior longitudinal fascicle

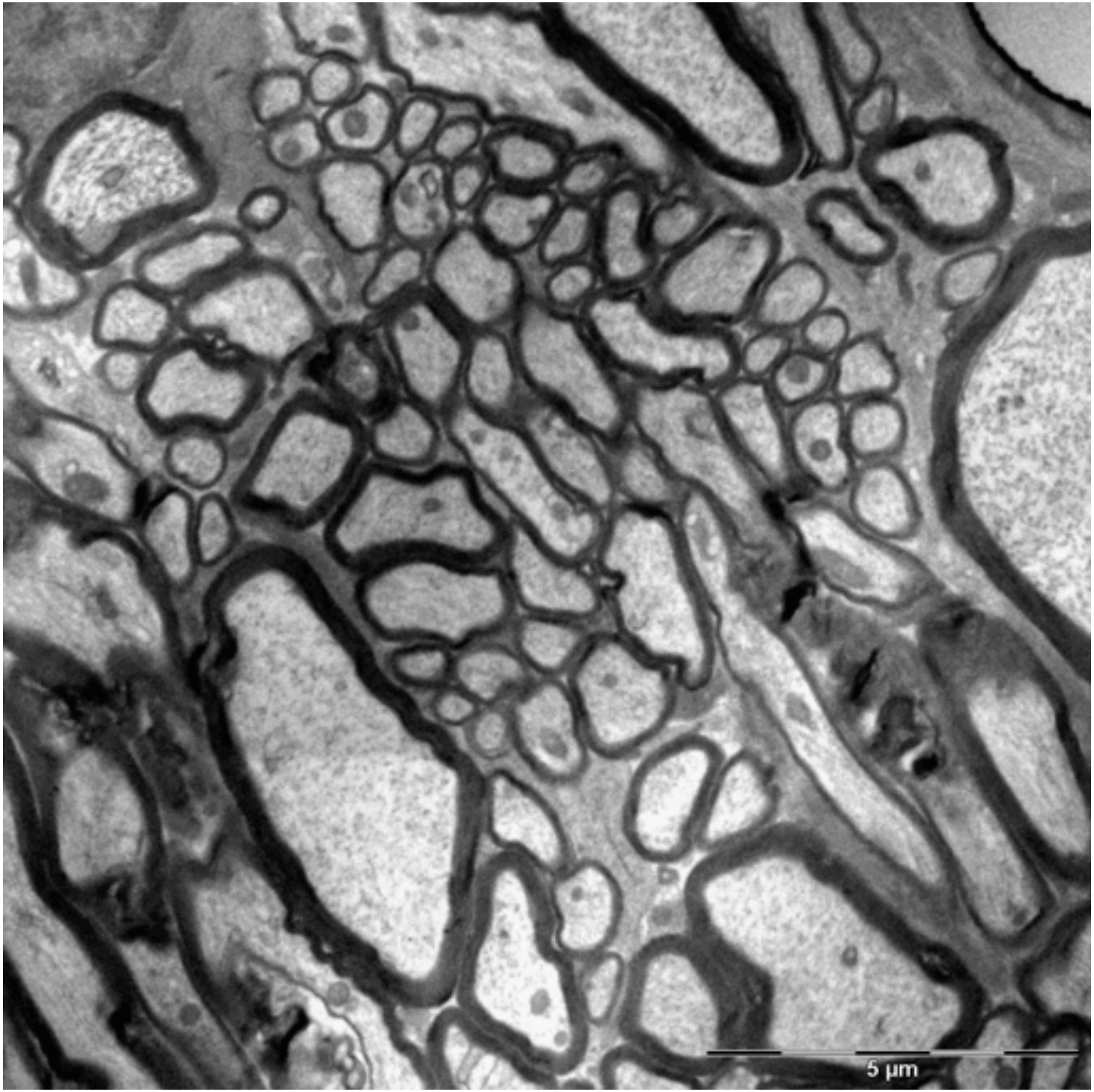
Human superior longitudinal fascicle



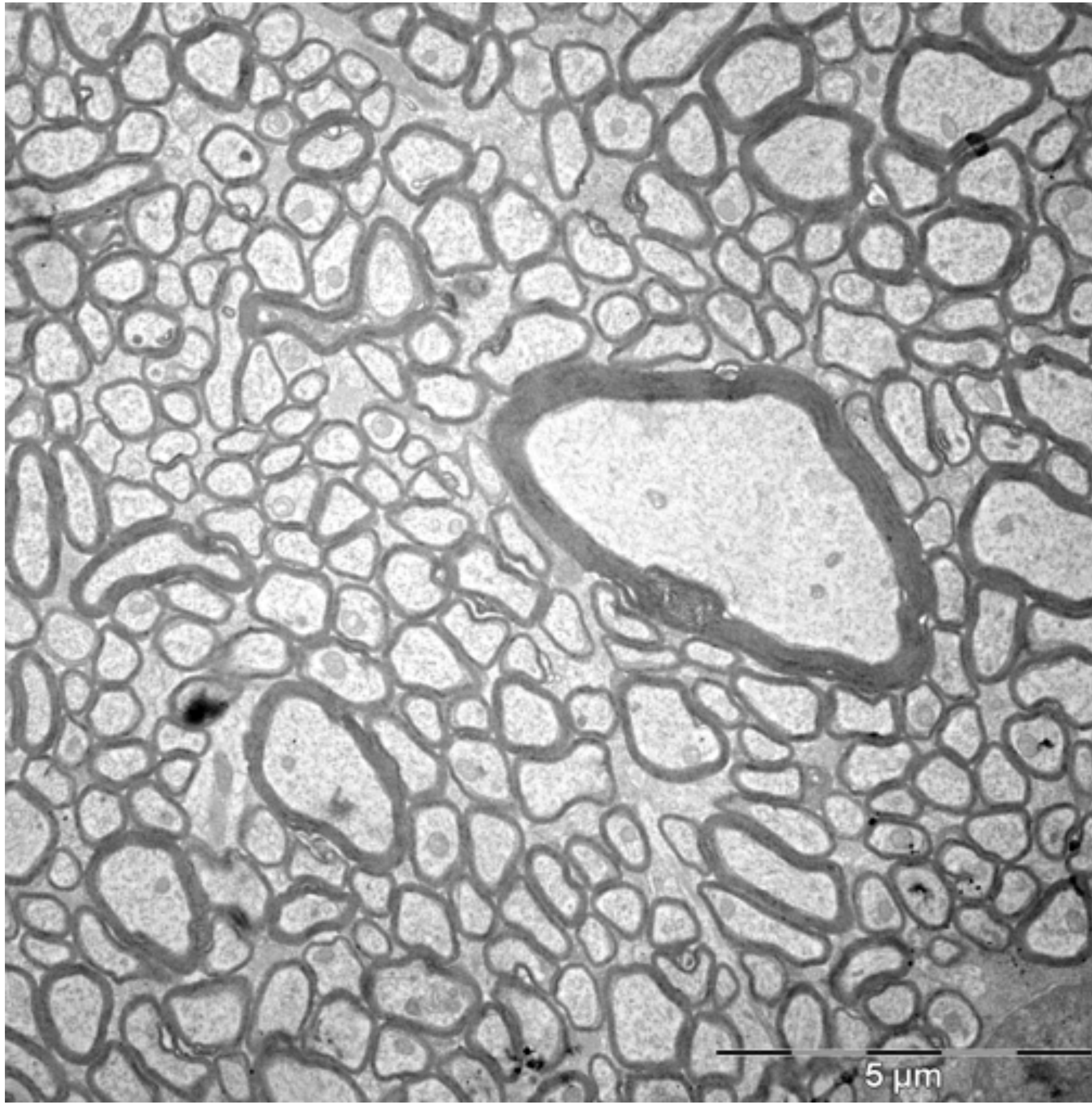
Human
uncinate
fascicle



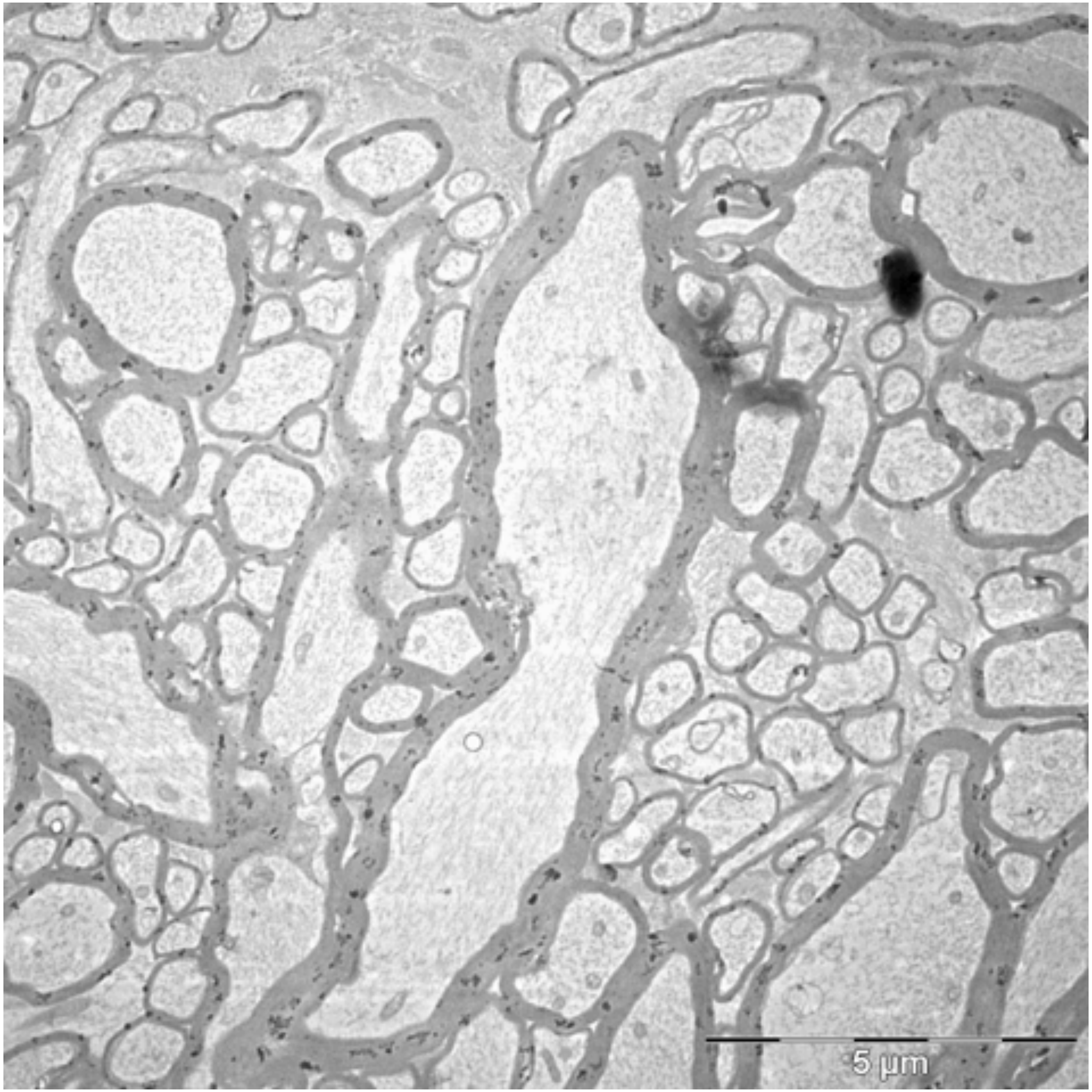
Monkey,
Corpus
callosum



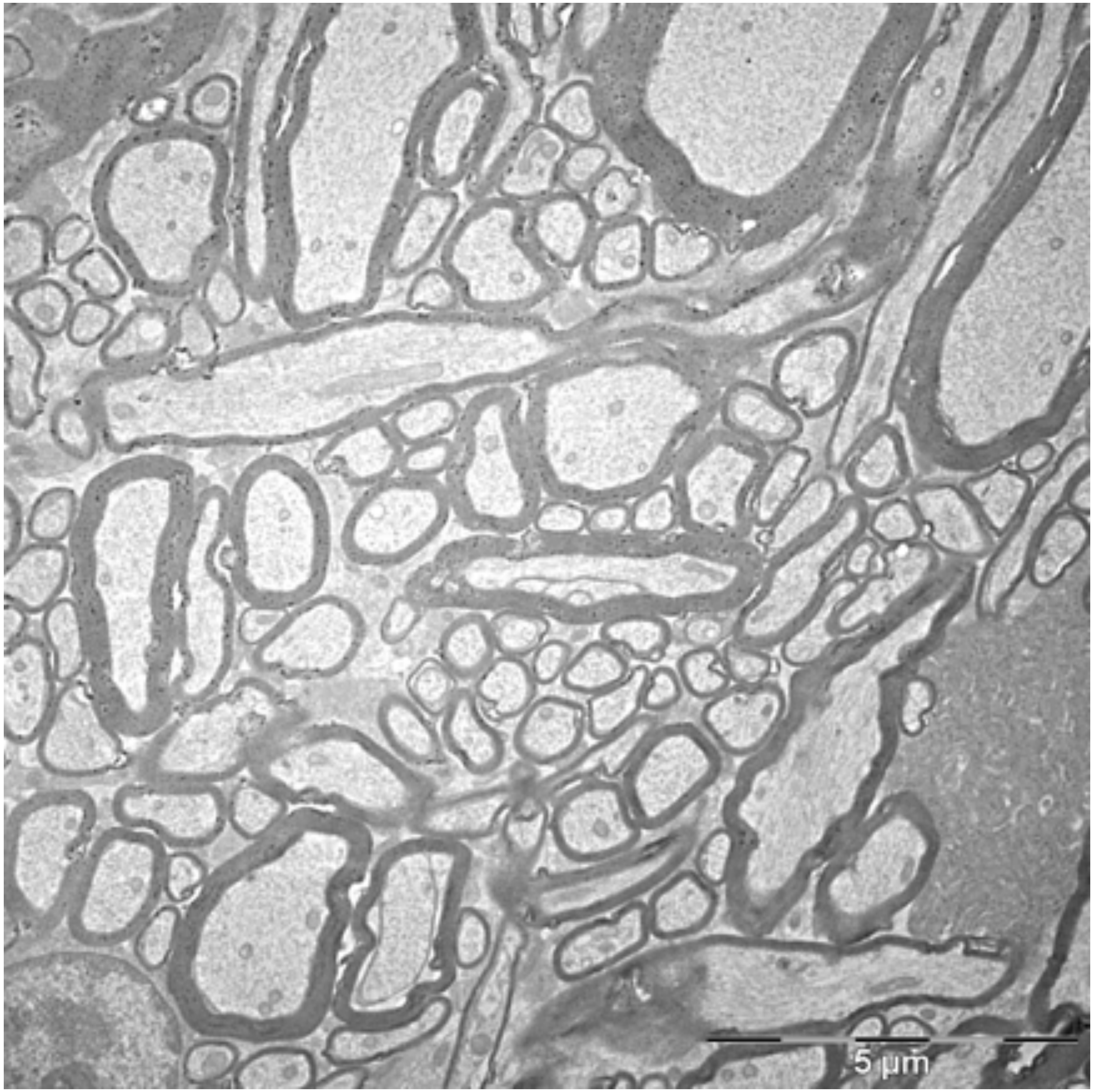
Monkey
Superior longitudinal
fascicle

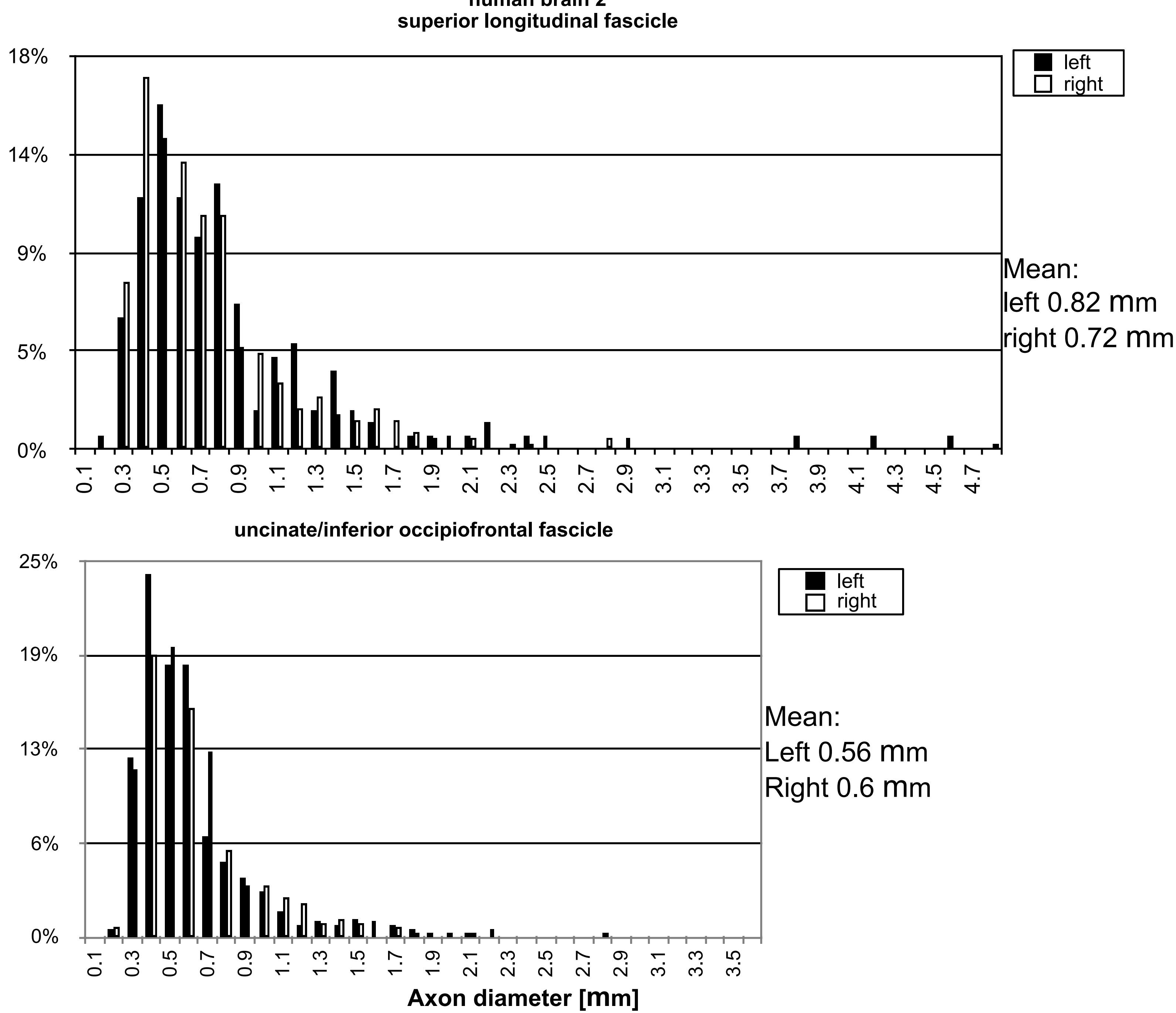


Monkey
Superior longitudinal
fascicle



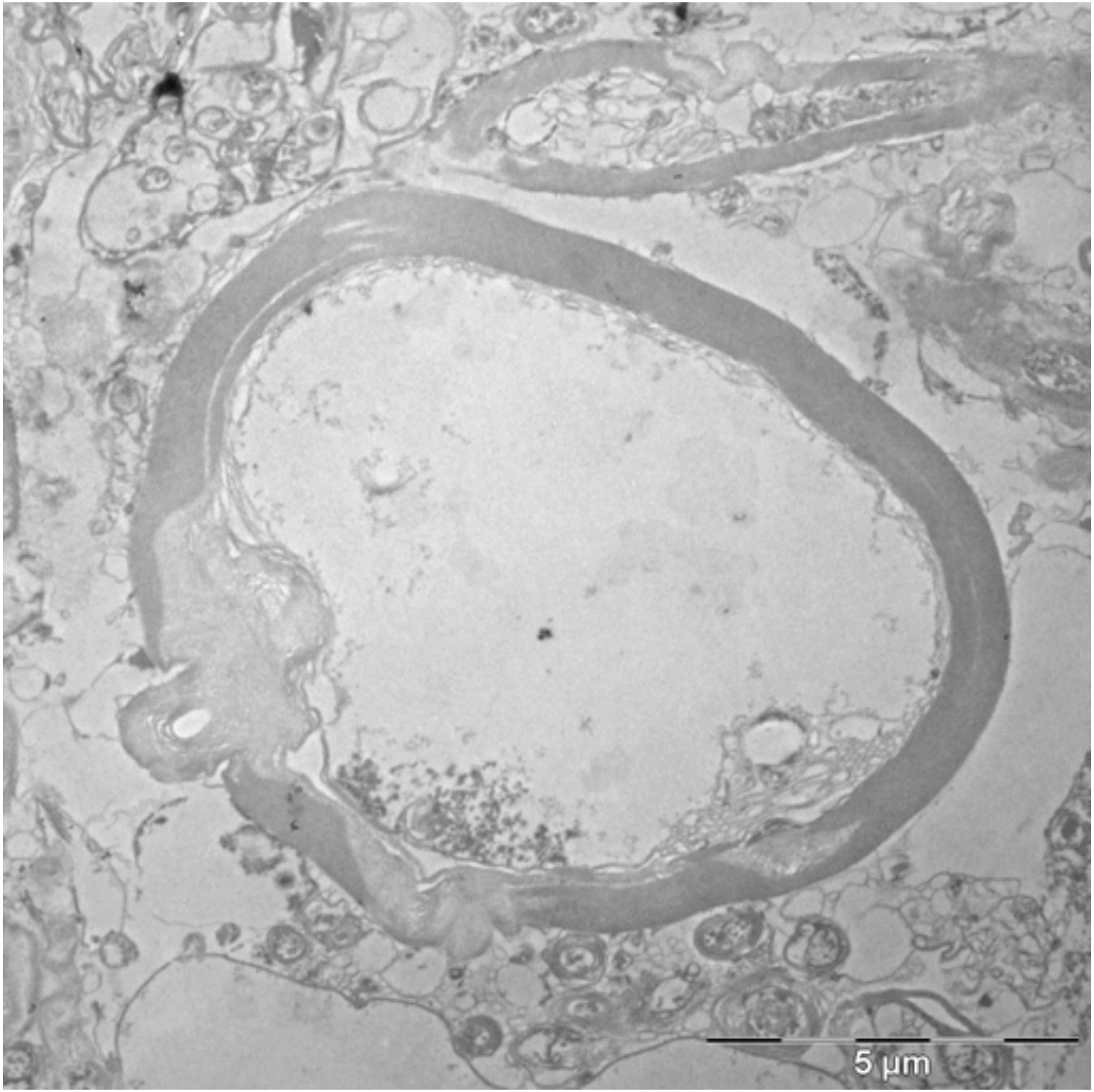
Monkey,
Superior longitudinal
fascicle



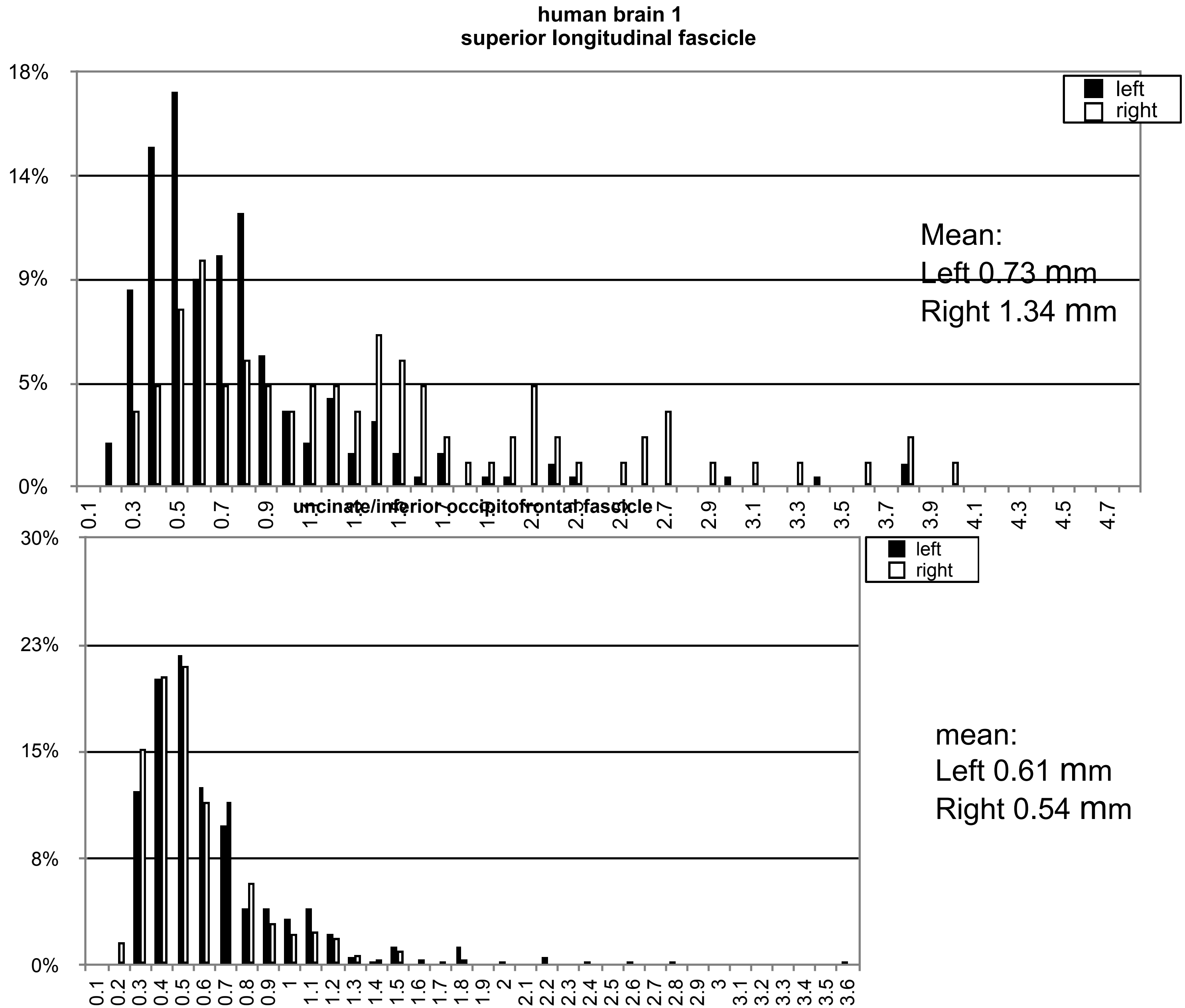


human brain 2
superior longitudinal fascicle
18%
14%
9%
5%
0%
left
right
Mean:
left 0.82 mm
right 0.72 mm
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
3.5
3.7
3.9
4.1
4.3
4.5
4.7
uncinate/inferior occipiofrontal fascicle
25%
19%
13%
6%
0%
left
right
Mean:
Left 0.56 mm
Right 0.6 mm
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
3.5
Axon diameter [mm]

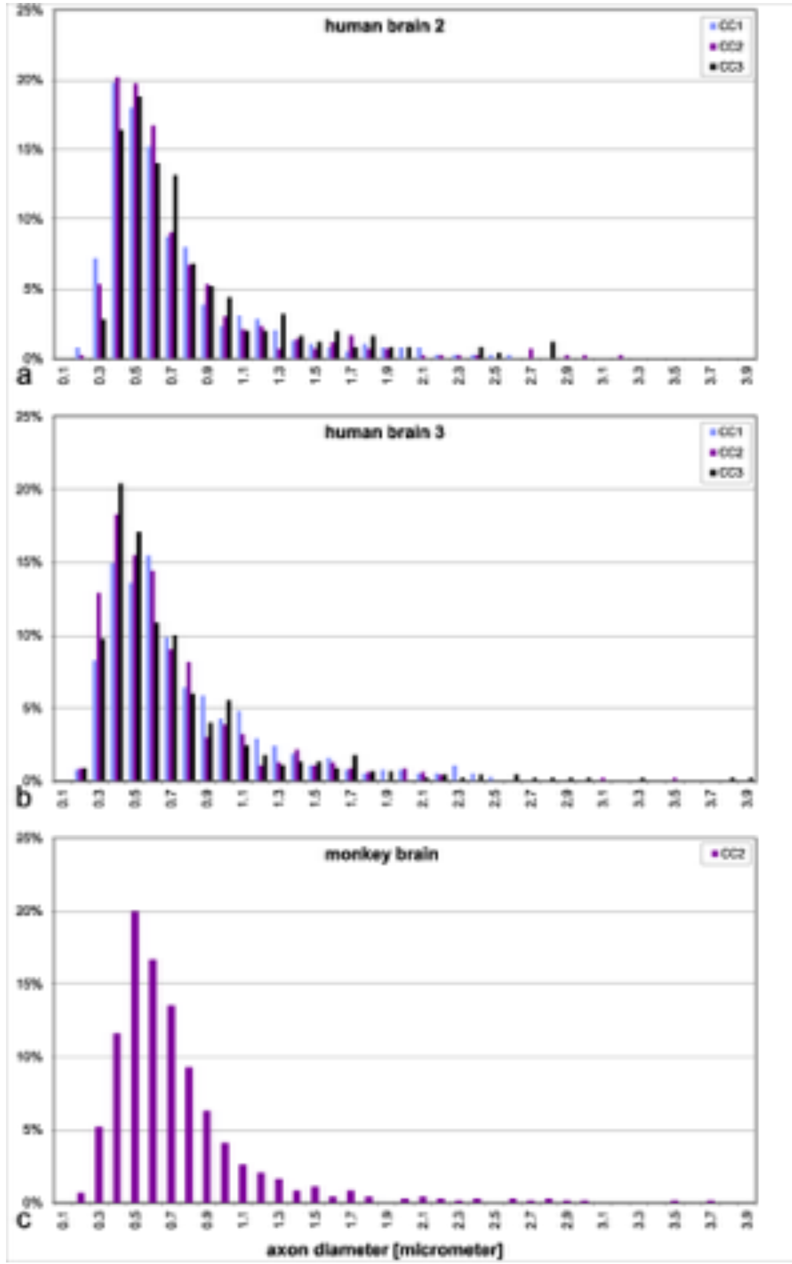
Human
superior
longitudinal
fascicle



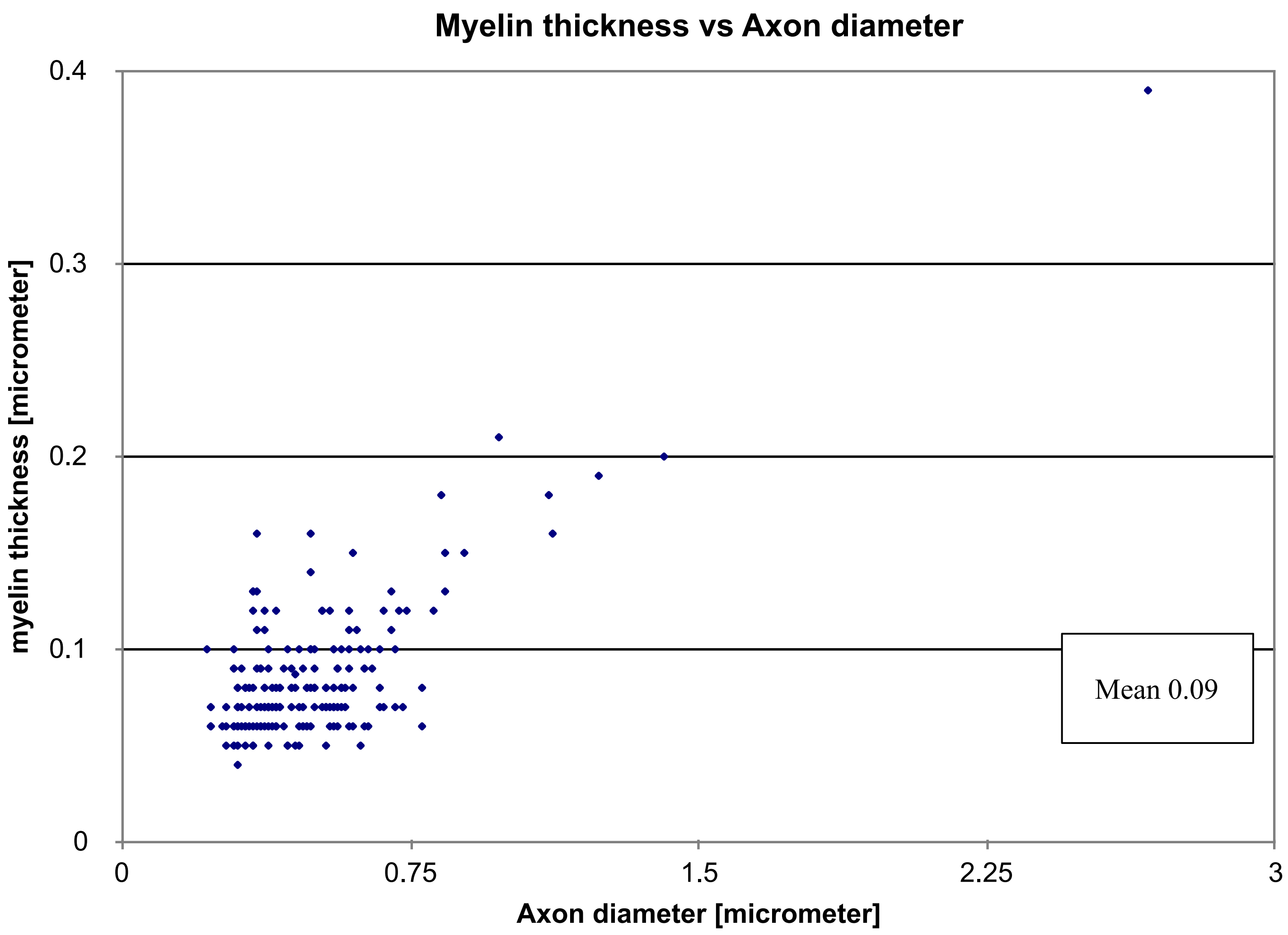
From
Liewald
and Schüz


human brain 1
superior longitudinal fascicle
left
right
Mean:
Left 0.73 mm
Right 1.34 mm
uncinate/inferior occipitofrontal fascicle
left
right
mean:
Left 0.61 mm
Right 0.54 mm

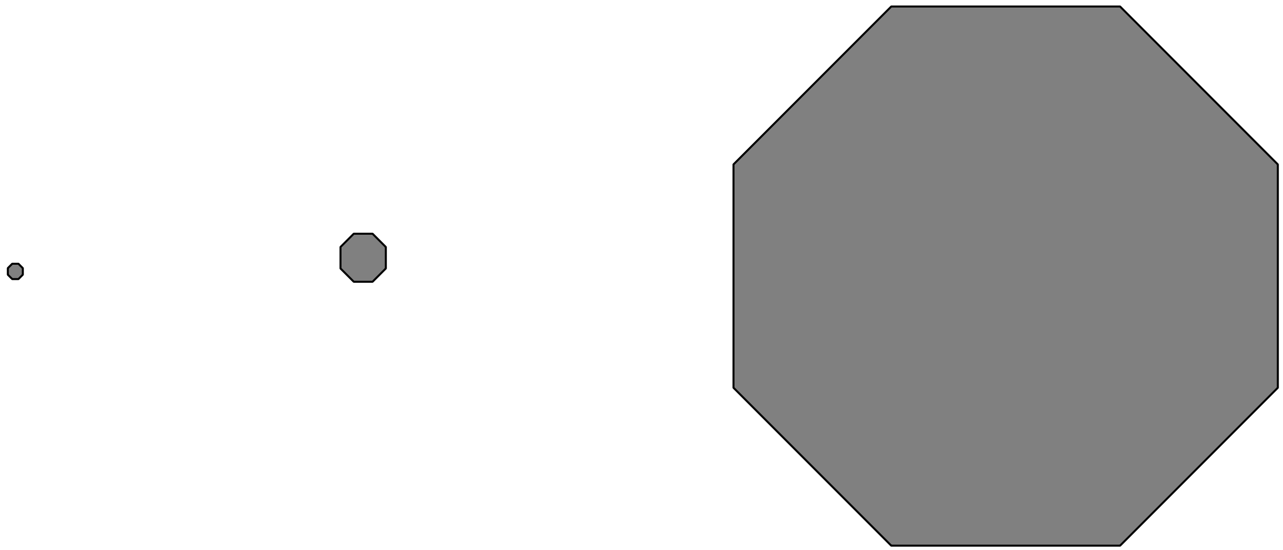
Corpus callosum



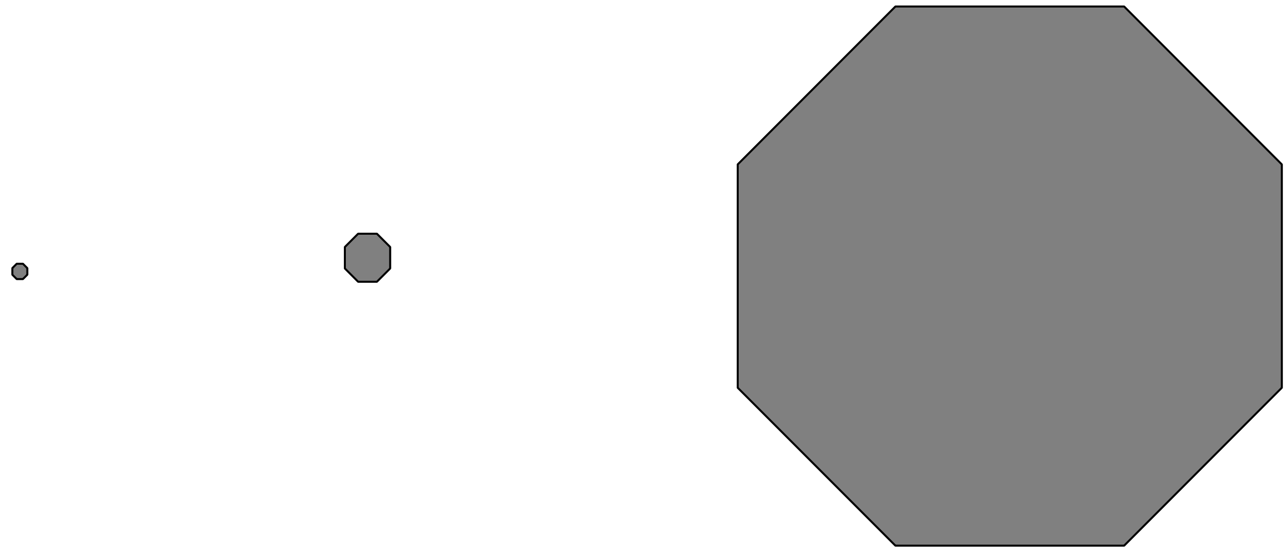
Mean values ~ 0.7 mm



Macaca mulatta, superior longitudinal fascicle



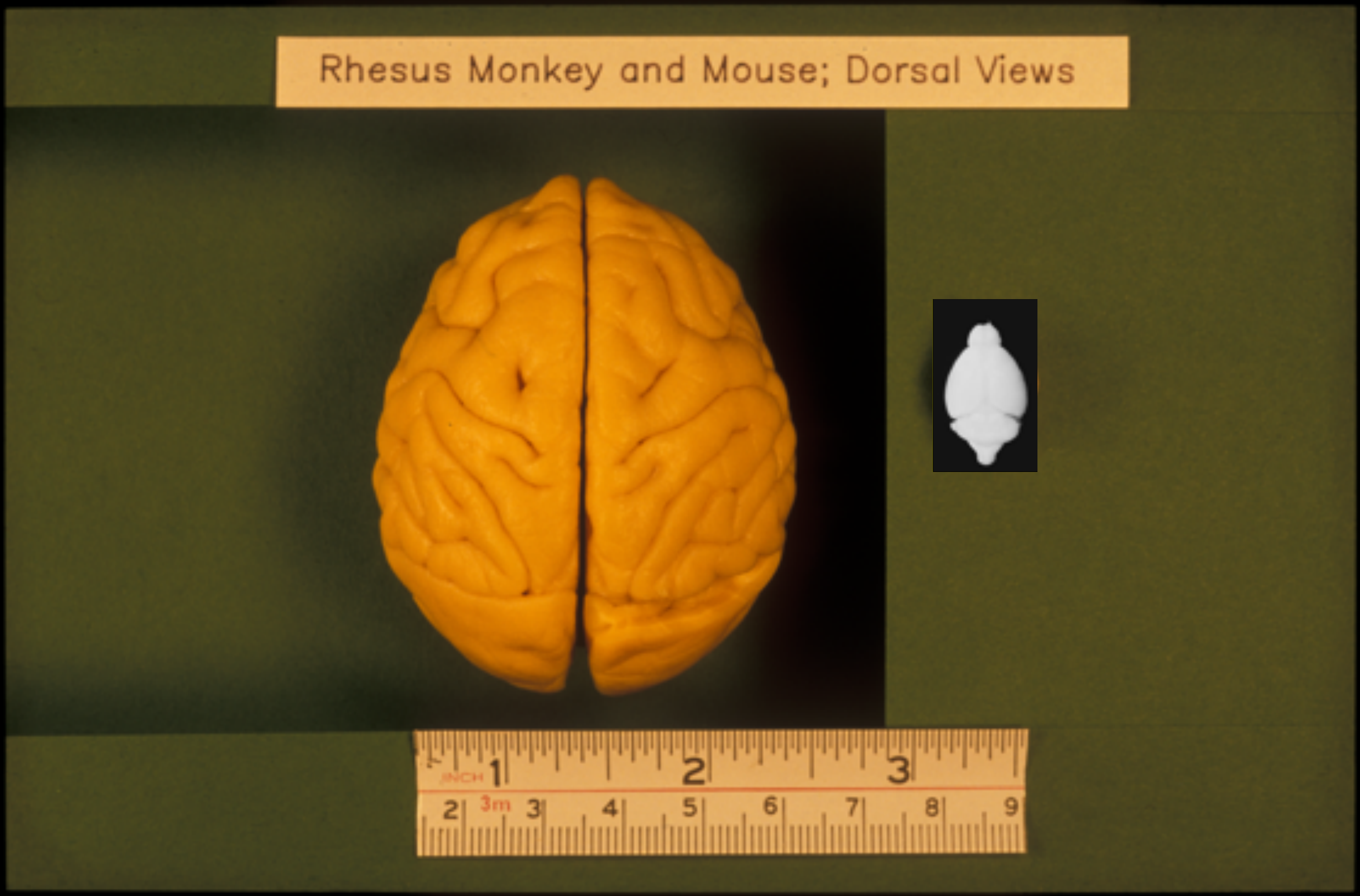
Diameters of myelinated axons between about 0.16 mm and 9 mm
(average < 1 mm), i.e. x 56



Diameters of myelinated axons between about 0.16 mm and 9 mm (average < 1 mm), i.e. x 56

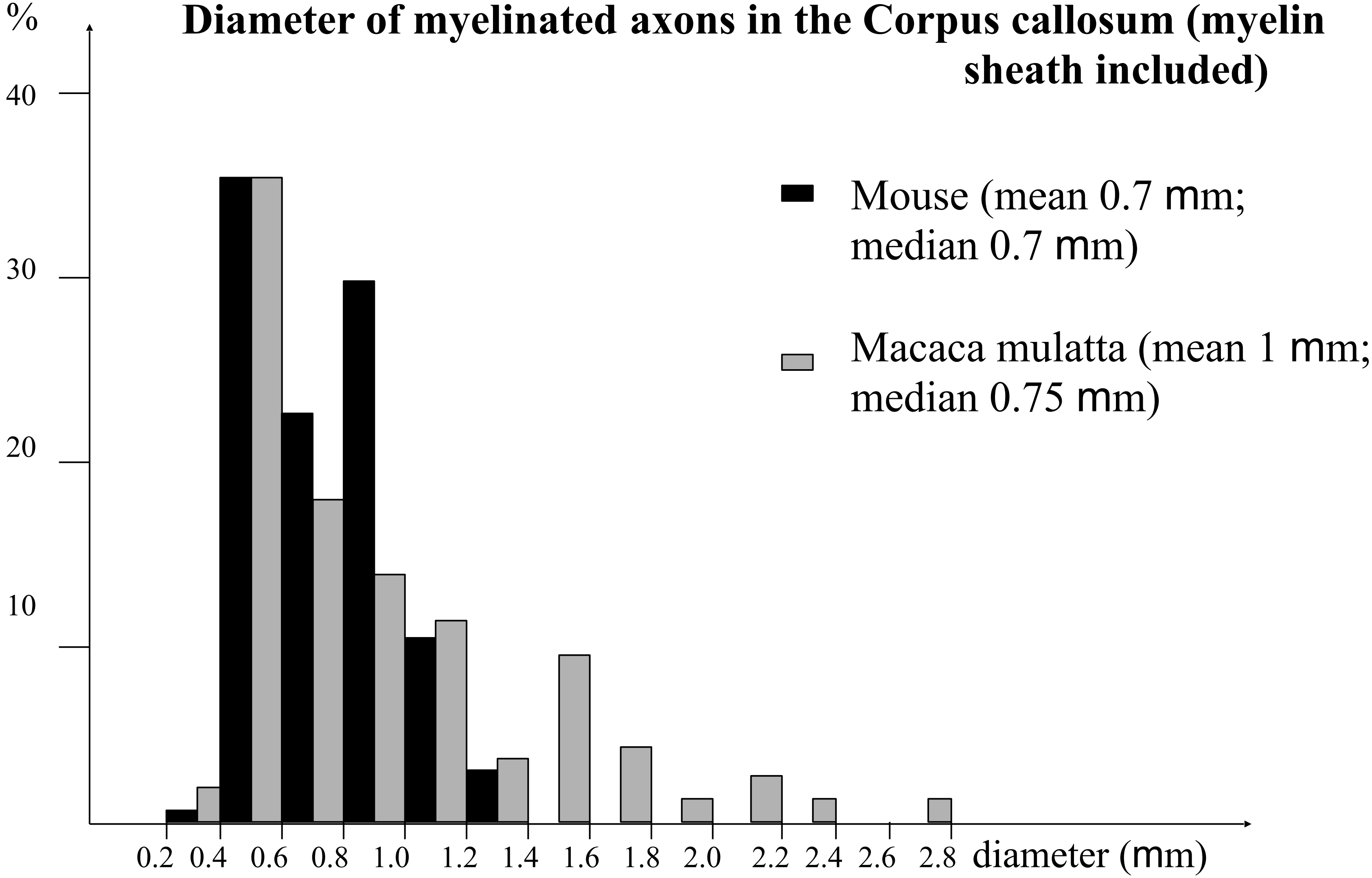
Measured conduction velocities (in monkeys) have been found to range between about 0.3 m/sec and 30 m/sec, i.e. x 100, probably due to inclusion of unmyelinated fibres

Axon diameter and brain size:
Corpus callosum in mouse and monkey



From Schüz and Jerison

Diameter of myelinated axons in the Corpus callosum (myelin sheath included)



From Schüz and Jerison

Conclusions on axonal thickness and functional aspects

Large calibre axons may contribute to time constancy with brain size in:

- brain rhythms
- propagation of oscillations over the neocortex
- synchronization between hemispheres

Conclusions on axonal diameter and functional aspects

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- propagation of oscillations over the neocortex
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Role of the large number of small calibre axons in large brains:

1. Keeping brain volume within reasonable limits
   (Ringo, Doty, Demeter, Simard, 1994)

2. Long conduction times may even have useful side effects
   (Miller 1996)

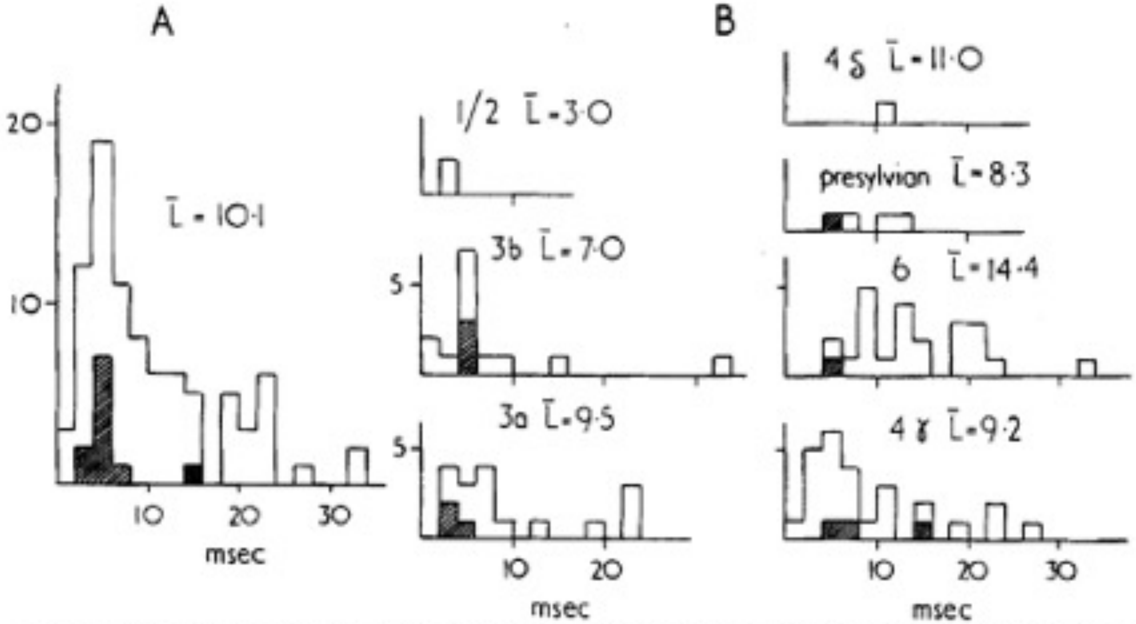
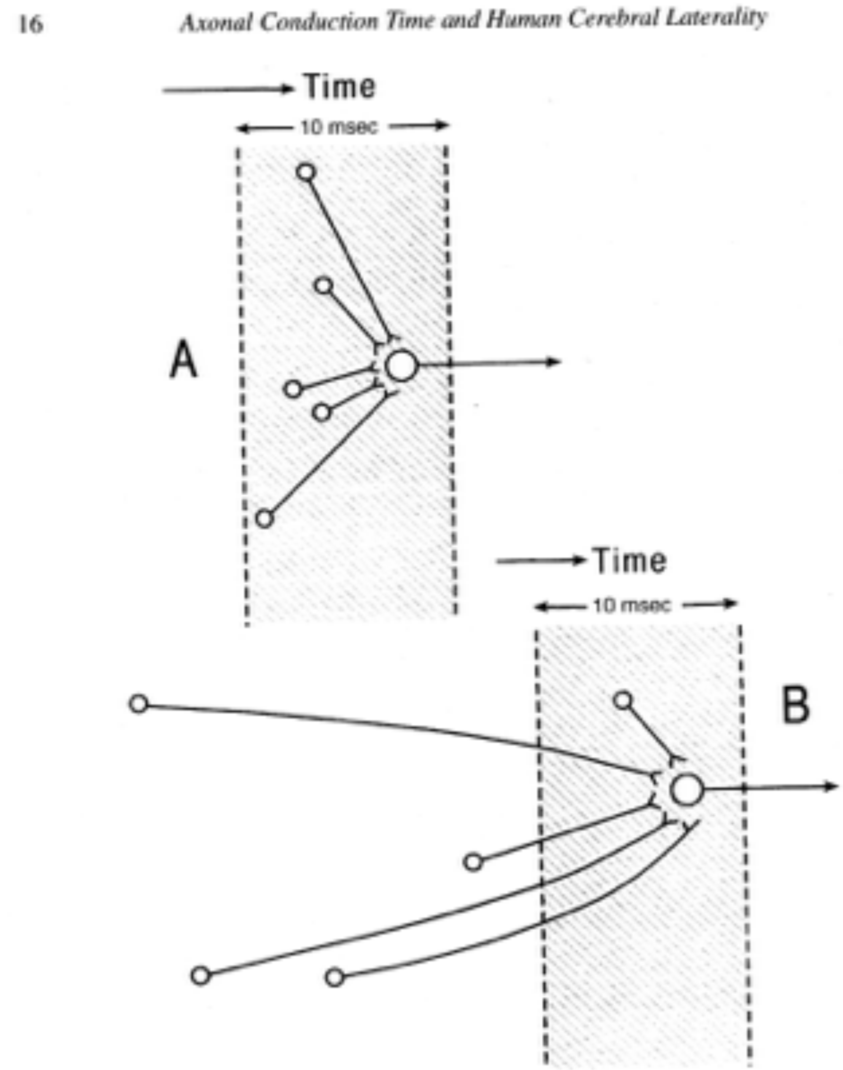


Fig. 5 *Histograms of latencies for 87 units responding antidromically to stimulation of the contralateral corpus callosum.* **(A) Total distribution. (B) Distribution in individual cytoarchitectural areas.** Above each histogram the average latency (L̄), for the neurons represented in that histogram, is given in msec. Cross-hatched areas represent neurons whose responses were proved antidromic by collision.

Increase in the range of conduction times can lead to sequence detection in neurons

From: Robert Miller, 1996

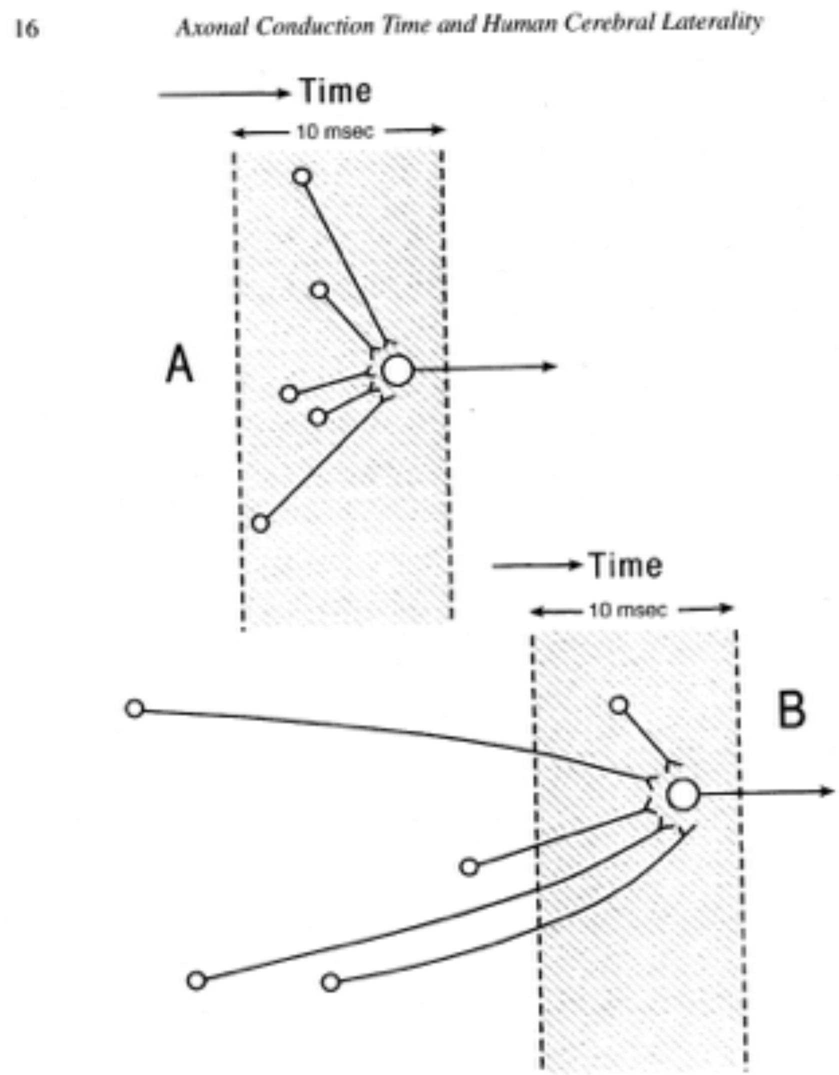


Increase in the range of conduction times can lead to sequence detection in neurons

(e.g. voice onset time difference between -t- and -d- of 50 msec)

From: Robert Miller, 1996

Later called „polychronization“ by Izhikevich (2006)



Summary

The particular structure of the cortex qualifies it as an associative memory and the formation of Hebbian cell assemblies and Abelesian synfire chains

Global cortical connectivity: high degree of divergence and convergence

Distant cortico-cortical fibres constitute only a few percent of the total number of cortico-cortical fibres in the white matter.

Only the maximum axonal diameter correlates with brain size

The range of axon diameters of cortico-cortical (myelinated) fibres (and with it conduction velocity) in the human cortical white matter differs by a factor of more than 50.

The large range of conduction times in large brains may be a prerequisite for some higher cognitive abilities, such as language

Propagation of activity over the cortex:

Synfire chain theory, Moshe Abeles (Corticonics, 1991)

Equilibrium between excitation and inhibition:

Günther Palm (University of Ulm, Germany)


Thank you!