511-evo-devo

Rick Gilmore

2021-10-08 08:12:52

- Fun
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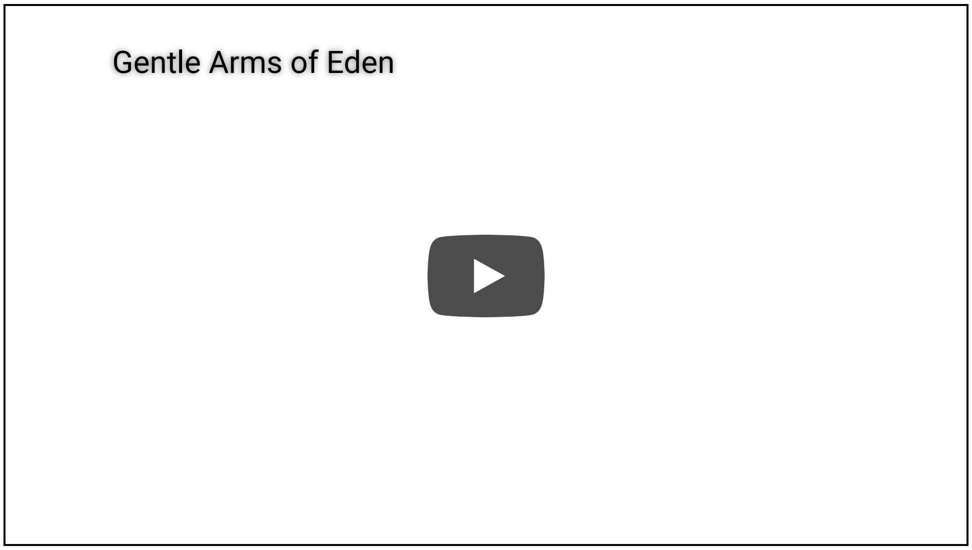
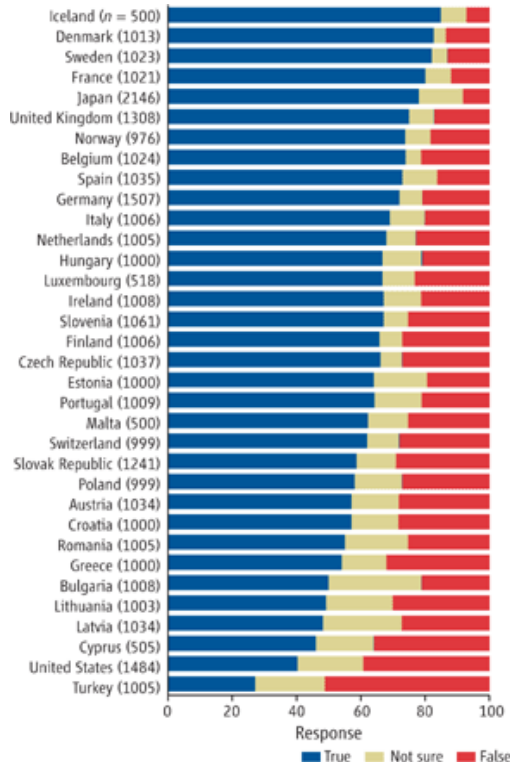
      - Changes in brain energetics (glucose utilization)
      - Gene expression across development
    - Summary of developmental milestones
      - Prenatal
      - Postnatal
    - How brain development clarifies anatomical structure
      - 3-4 weeks
      - 4 weeks
      - ~4 weeks
      - 6 weeks
      - Beyond 6+ weeks
      - Organization of the brain
      - From structural development to functional development
- References

Fun



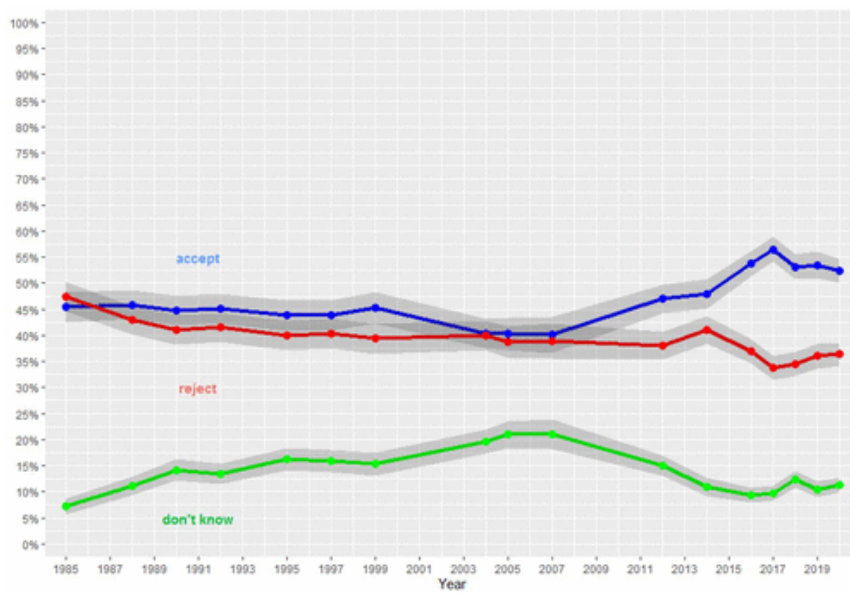
Evolution

Public acceptance of evolution



(Miller, Scott, & Okamoto, 2006) (http://dx.doi.org/10.1126/science.1126746)

- In U.S., majority now "accept"
- Increase over last decade



(Miller et al., 2021) (http://dx.doi.org/10.1177/09636625211035919)

Types of evidence

- Fossil
  - Fossil dating
- Geological
  - Where fossils are found relative to one another
  - How long it takes to form layers
- Genetic
  - Rates of mutation
- Anatomical
  - Homologous structures across species

> **Nothing in Biology Makes Sense except in the Light of Evolution**
>
> *"Seen in the light of evolution, biology is, perhaps, intellectually the most satisfying and inspiring science. Without that light, it becomes a pile of sundry facts some of them interesting or curious, but making no meaningful picture as a whole."*

(Dobzhansky, 1973) (http://dx.doi.org/10.2307/4444260)

Why Gilmore thinks the theory so controversial (in the U.S.)

- Contradicts verbatim/non-metaphorical reading of some religious texts
- Makes humans seem less special
- Time scales involved beyond human experience
- Scientific method vs. other ways of knowing
- Found in nature ≠ good for human society
- Few negative consequences of 'disbelief'
- U.S. culture individualistic, skeptical, anti-elitist, anti-intellectual
- Lower levels of religious belief among U.S. scientists (http://news.rice.edu/2015/12/03/first-worldwide-survey-of-religion-and-science-no-not-all-scientists-are-atheists/)
- Politics (http://www.people-press.org/2009/07/09/section-4-scientists-

politics-and-religion/)

- A minority of citizens support teaching evolution-only (http://www.pbs.org/wgbh/nova/blogs/education/2015/12/evolutionschools/)
- Majority of classroom teachers aren't strong advocates (https://www.sciencedaily.com/releases/2011/01/110127141657.htm)

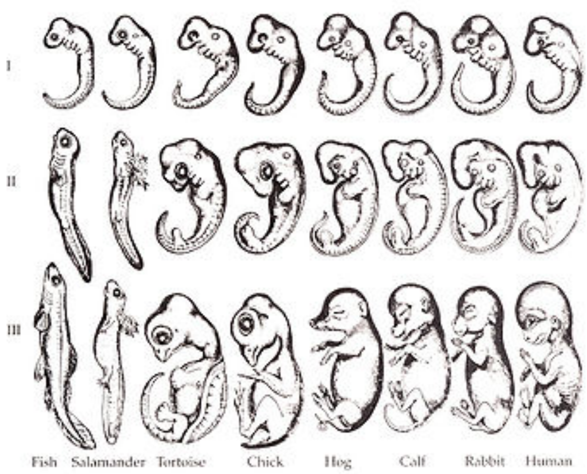
> A structural equation model indicates that increasing enrollment in baccalaureate-level programs, exposure to college-level science courses, a declining level of religious fundamentalism, and a rising level of civic scientific literacy are responsible for the increased level of public acceptance.
>
> (Miller et al., 2021) (http://dx.doi.org/10.1177/09636625211035919)

Evolution and development

Ontogenesis and phylogenesis

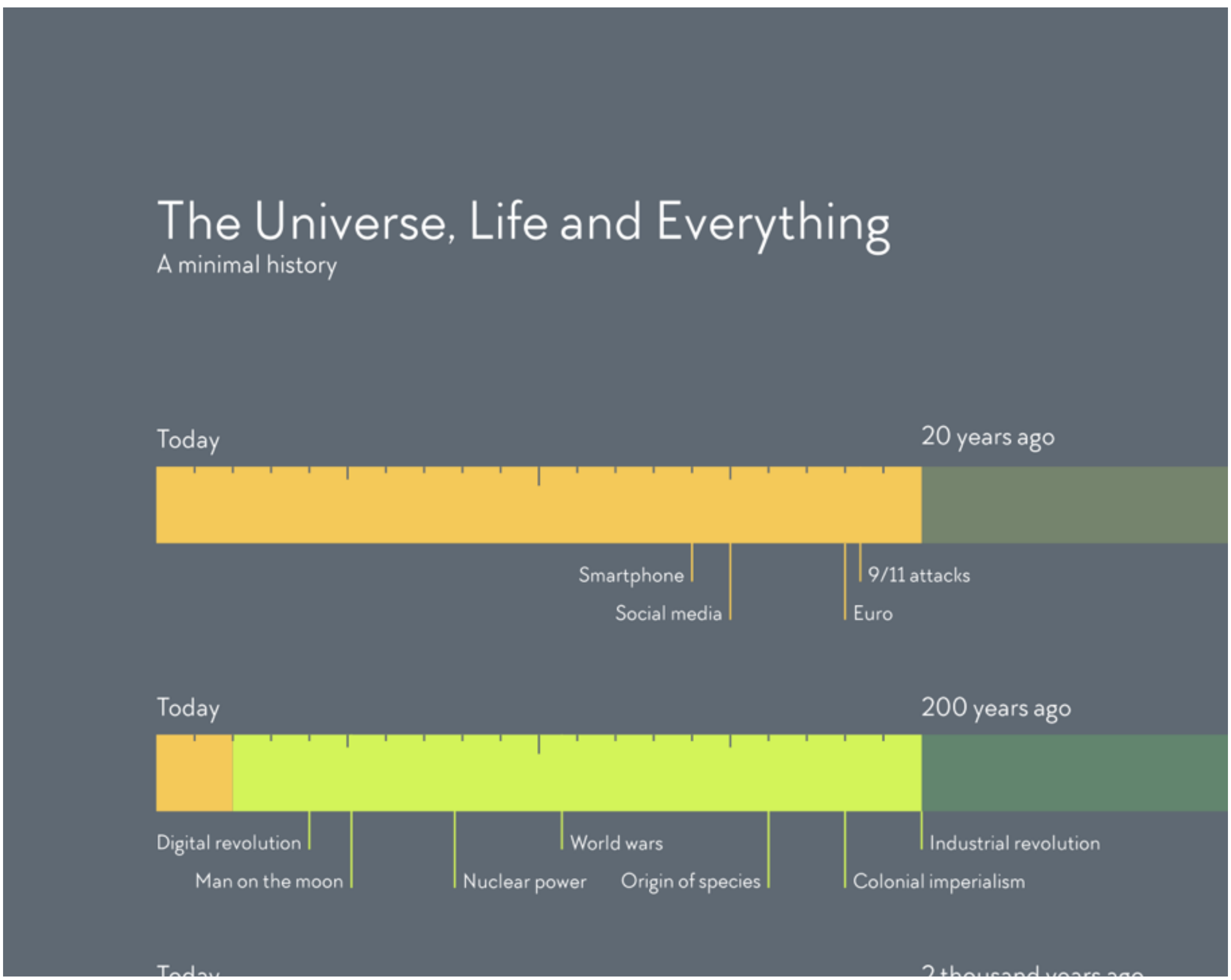
- *Ontogenesis*
  - Development within lifetimes, history of individuals
- *Phylogenesis*
  - Change across lifestimes, history of species

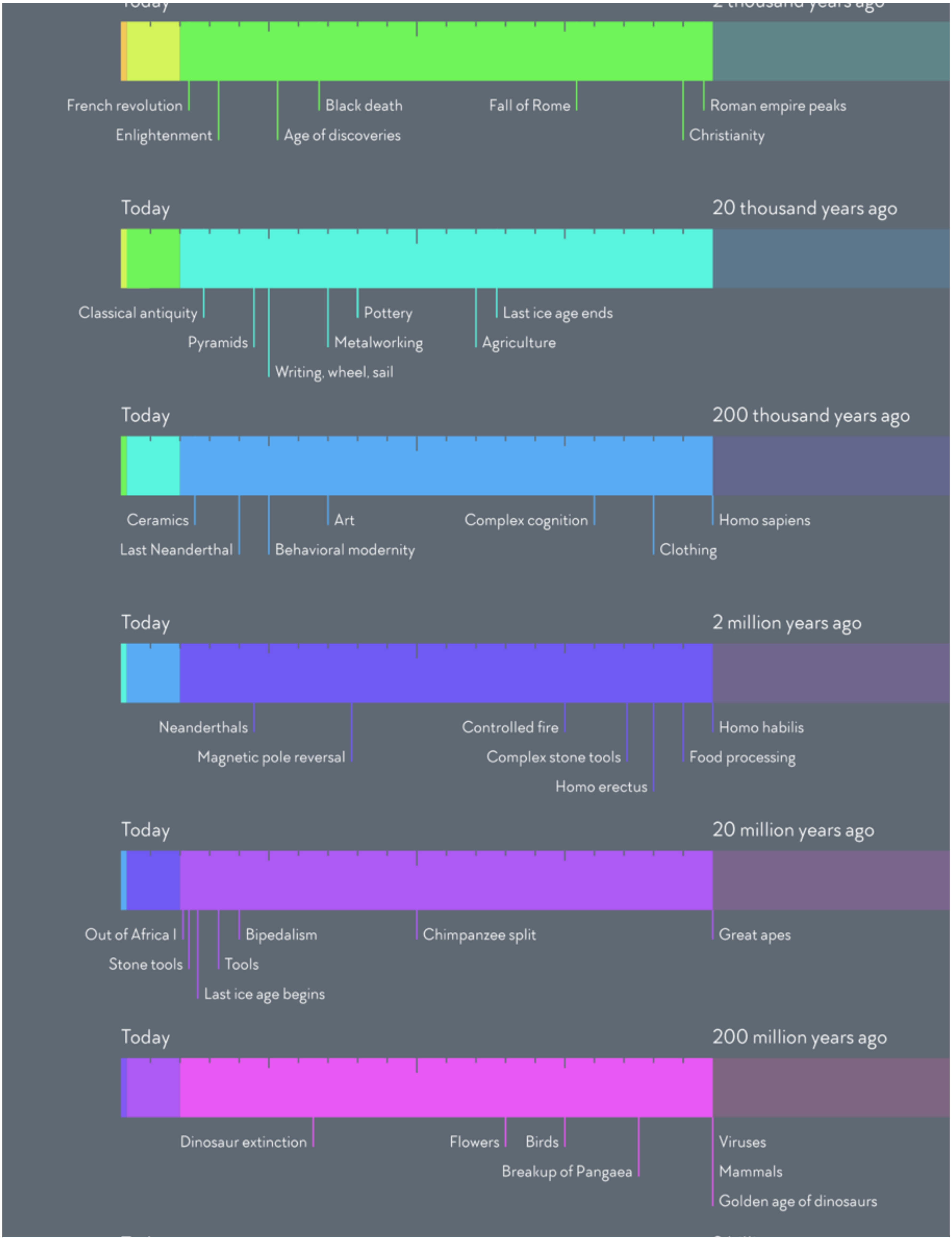
Ontogeny does not recapitulate phylogeny (Haeckel (https://en.wikipedia.org/wiki/Ernst_Haeckel)), but…

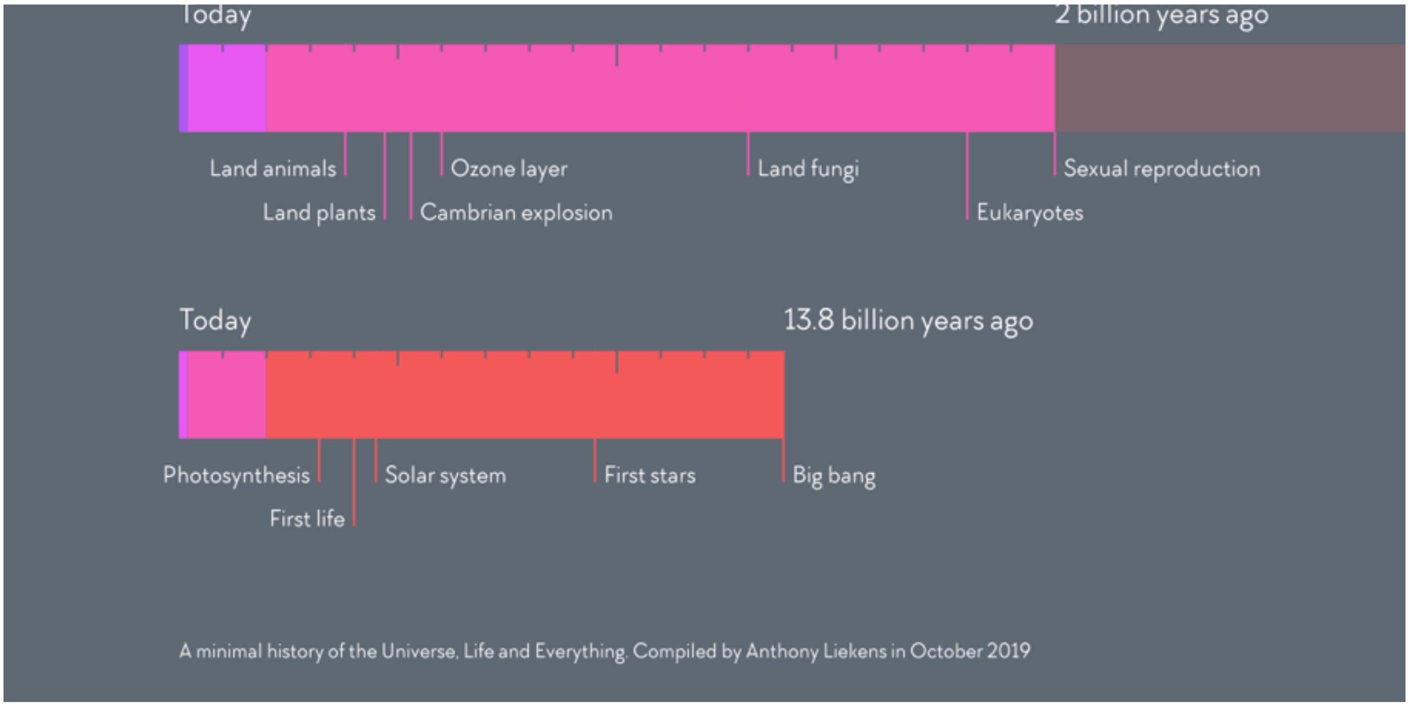


Source: Wikipedia

Complex multicellular life emerged “recently”




French revolution
Enlightenment
Black death
Age of discoveries
Fall of Rome
Roman empire peaks
Christianity
Today
20 thousand years ago
Classical antiquity
Pyramids
Writing, wheel, sail
Pottery
Metalworking
Last ice age ends
Agriculture
Today
200 thousand years ago
Ceramics
Last Neanderthal
Art
Behavioral modernity
Complex cognition
Clothing
Homo sapiens
Today
2 million years ago
Neanderthals
Magnetic pole reversal
Controlled fire
Complex stone tools
Homo erectus
Homo habilis
Food processing
Today
20 million years ago
Out of Africa I
Stone tools
Last ice age begins
Tools
Bipedalism
Chimpanzee split
Great apes
Today
200 million years ago
Dinosaur extinction
Flowers
Birds
Breakup of Pangaea
Viruses
Mammals
Golden age of dinosaurs



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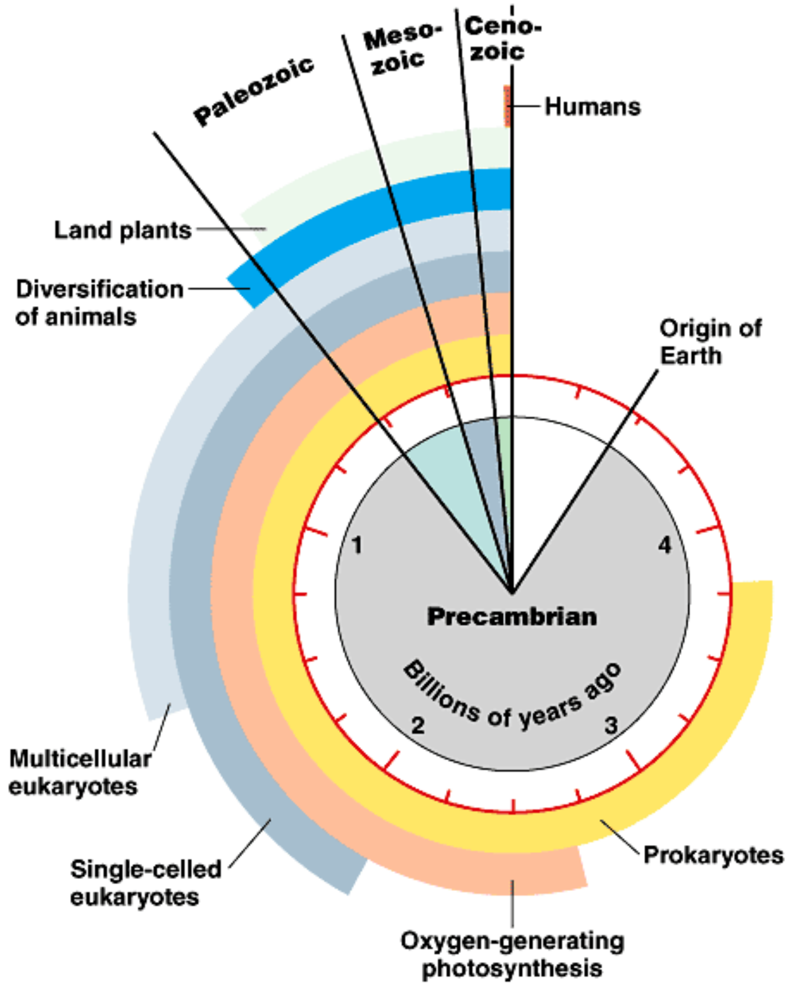


Source: http://www.zo.utexas.edu/faculty/sjasper/images/26.2.gif (http://www.zo.utexas.edu/faculty/sjasper/images/26.2.gif)

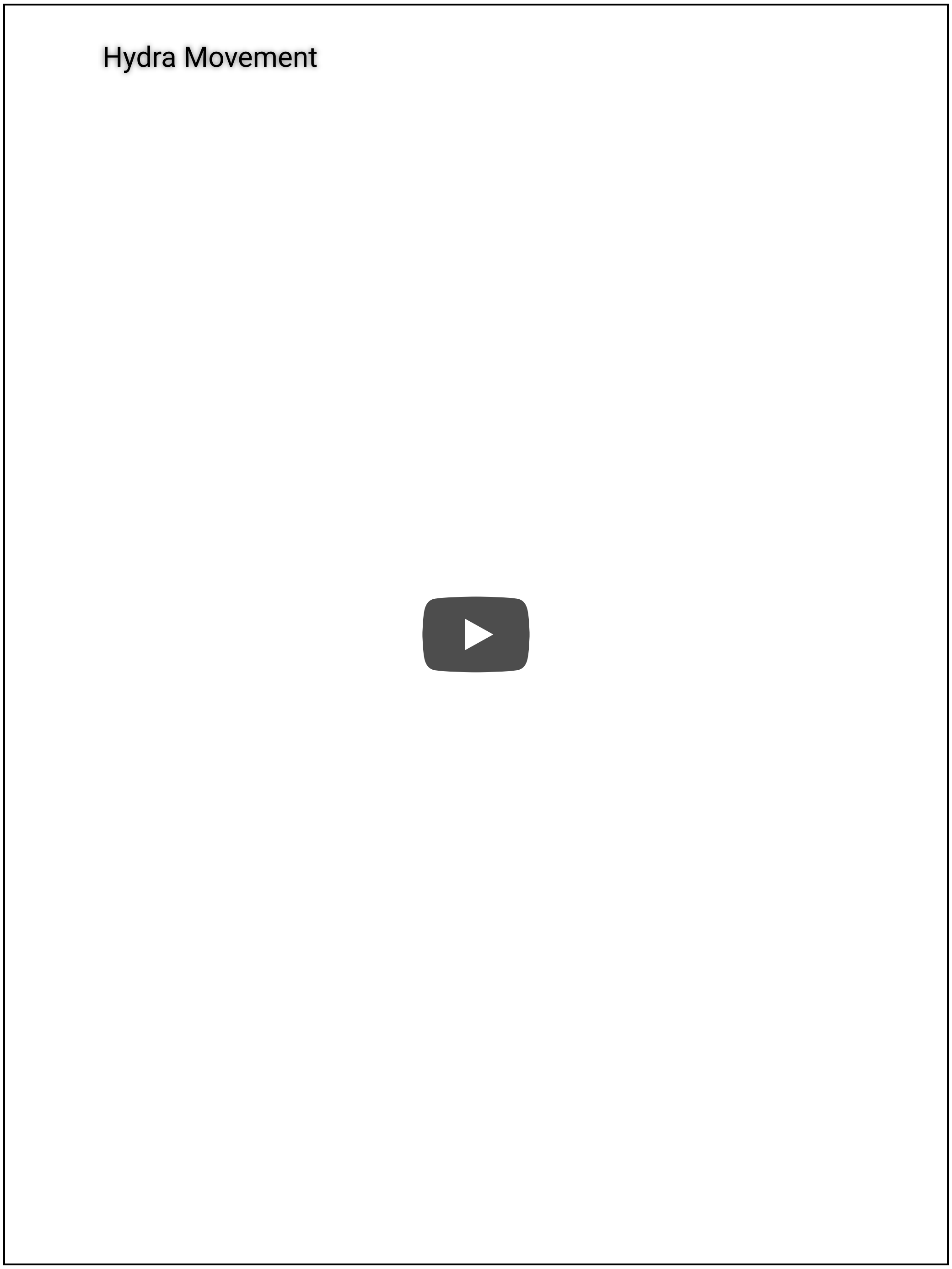
Nervous system architectures

How nervous systems differ

- Body symmetry
  - radial
  - bilateral

Source: (Arendt, Tosches, & Marlow, 2016) (https://doi.org/10.1038/nrn.2015.15)

An animal with a nerve “net”



- Segmentation
- Cephalization (concentration of sensory & neural structures in anterior portion of body)
- Encasement in bone (vertebrates)
- Centralized vs. distributed function

Cephalopods have “intelligent arms”

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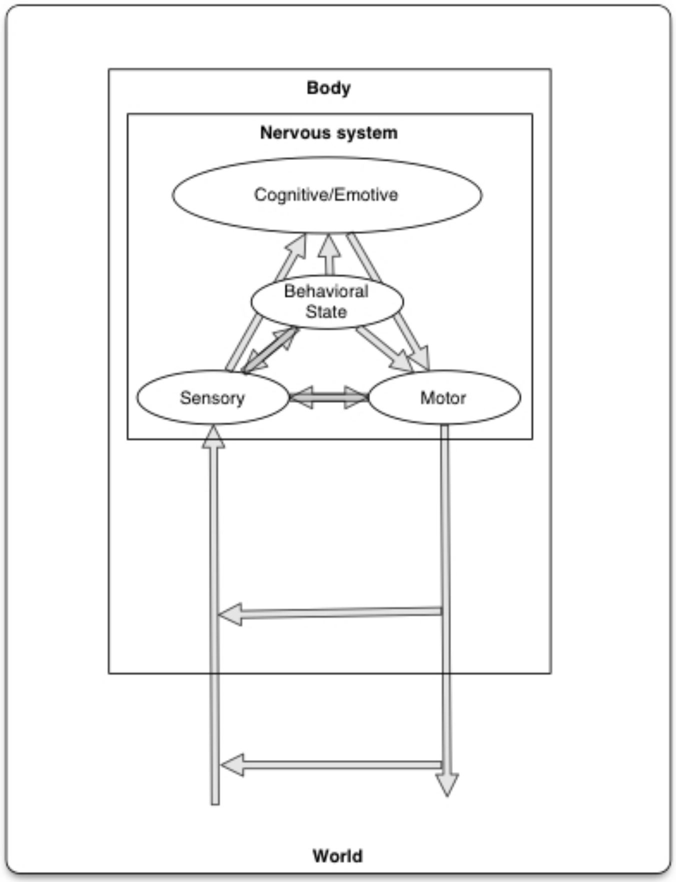
strong pinch applied with surgical forceps at the distal point indicated at T = 0 s; note that the arm not only contracts but also curls in the upper third. B. The full time course (20 s) of the response to a pinch in the arm. C. The response of an isolated arm to immersion of the distal ~ 1 cm of the arm in tap water at T = 0 s. D. The response over the next 20 s. The withdrawal of the arm is shown (B and D) by plotting the vertical location of the arm tip in relation to its original starting point in the resting state. The change in position is expressed as a percentage of the vertical length of the arm (tip = 100% and most proximal point = 0%) in the resting state visible in the video frame (T = 0 s). Note that the time to reach maximal shortening in response to both stimuli is more rapid than the time taken for the arm to return towards the resting length.

FEEDBACK

The essentials of biological computation

- Ingestion
- Defense
- Reproduction



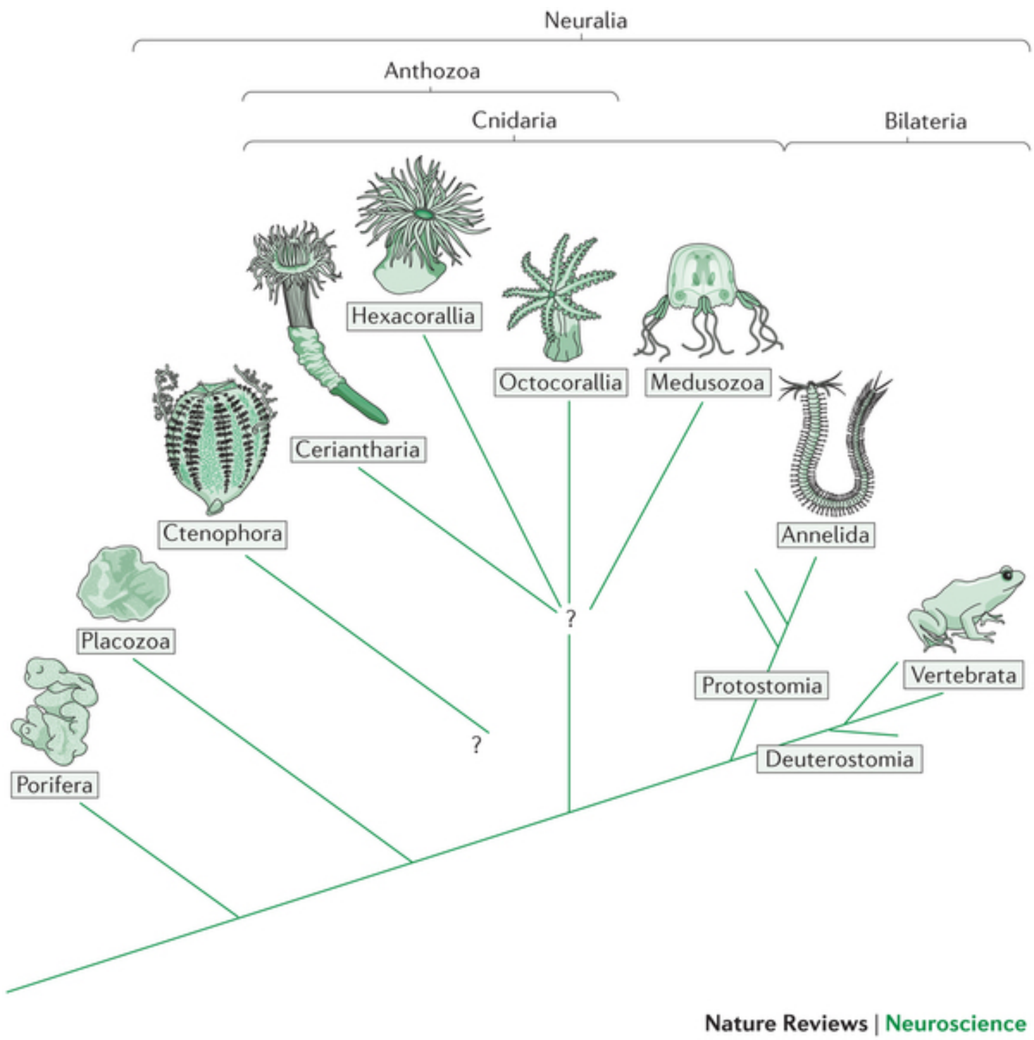
Information processing universals

- Sense/detect via sensors
  - Specialize by information source/type
  - Specialize by target location
    - Interoceptive
    - Exteroceptive
- Analyze, evaluate, decide
  - Current state
    - World
    - Organism
  - Current goals
  - Past state(s)
- Act
  - Move body

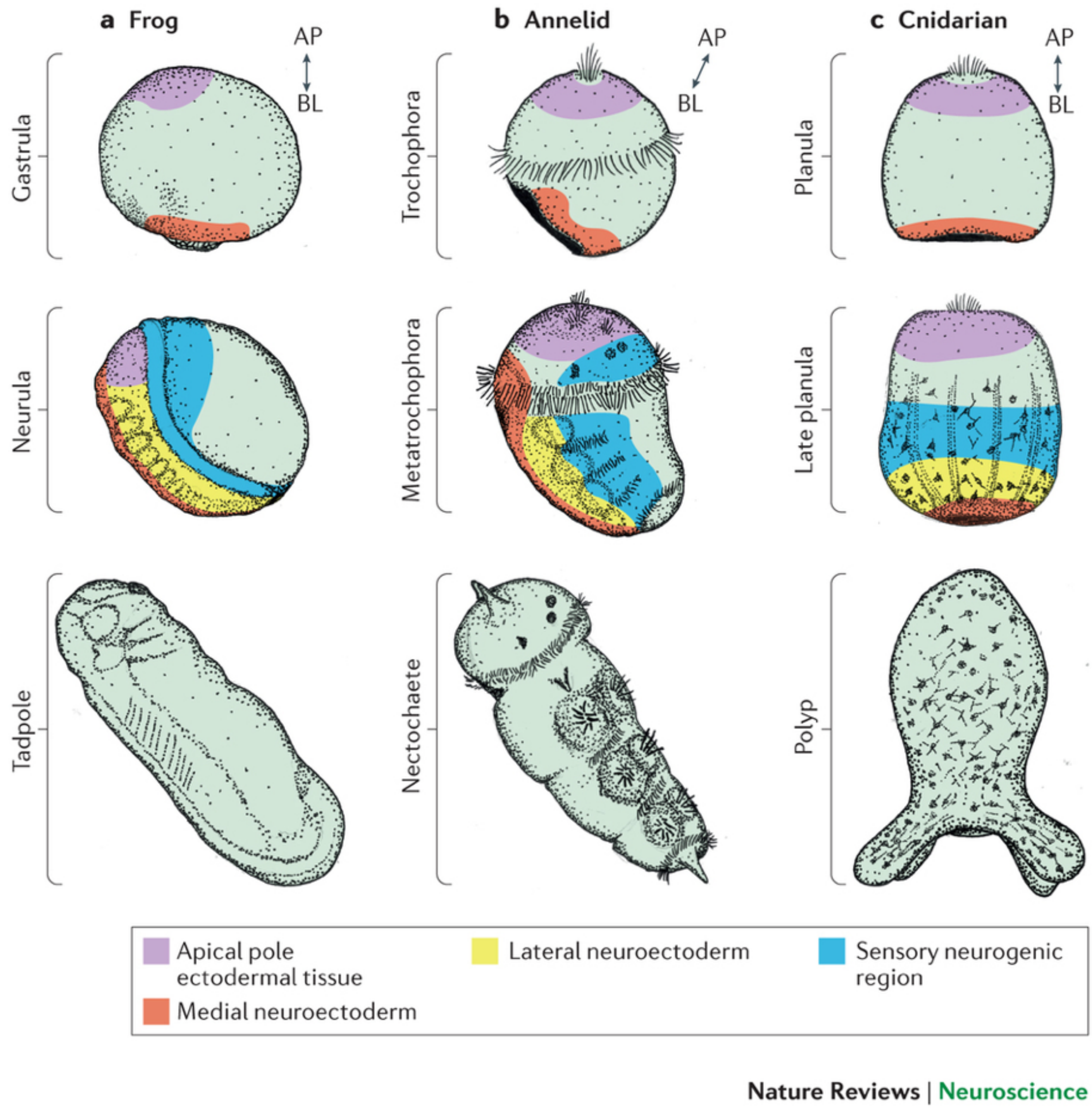
    - Approach/avoid
    - Manipulate
    - Ingest
    - Signal
  - Change physiological state

From nerve net to nerve ring, nerve cord, and brain

(Arendt, Tosches, & Marlow, 2016) (http://doi.org/10.1038/nrn.2015.15)



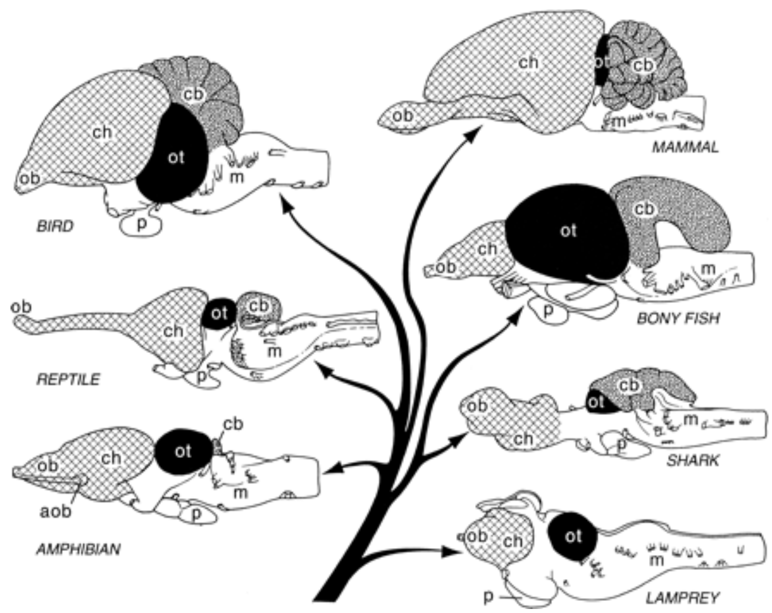
(Arendt, Tosches, & Marlow, 2016) (http://doi.org/10.1038/nrn.2015.15)



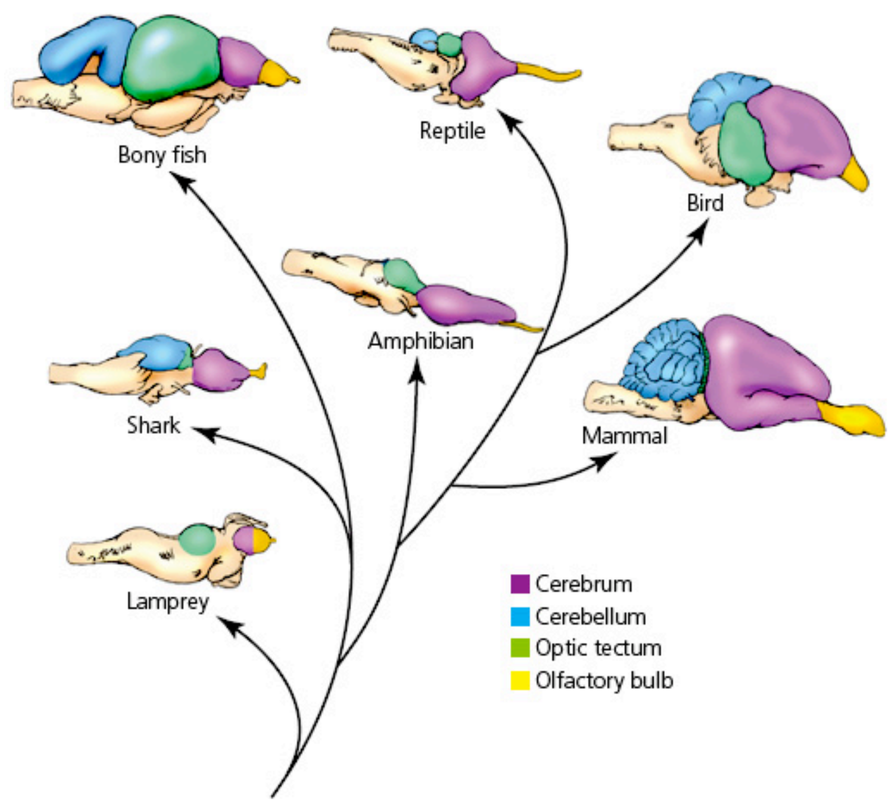
(Arendt, Tosches, & Marlow, 2016) (http://doi.org/10.1038/nrn.2015.15)

- Neurons and nervous systems 520-570 M years old
- Diverse nervous systems show developmental similarities at molecular level

Vertebrate CNS organization



(Northcutt, 2002) (http://doi.org/10.1093/icb/42.4.743)



http://www.bio.miami.edu/dana/pix/vertebrate_brains.jpg
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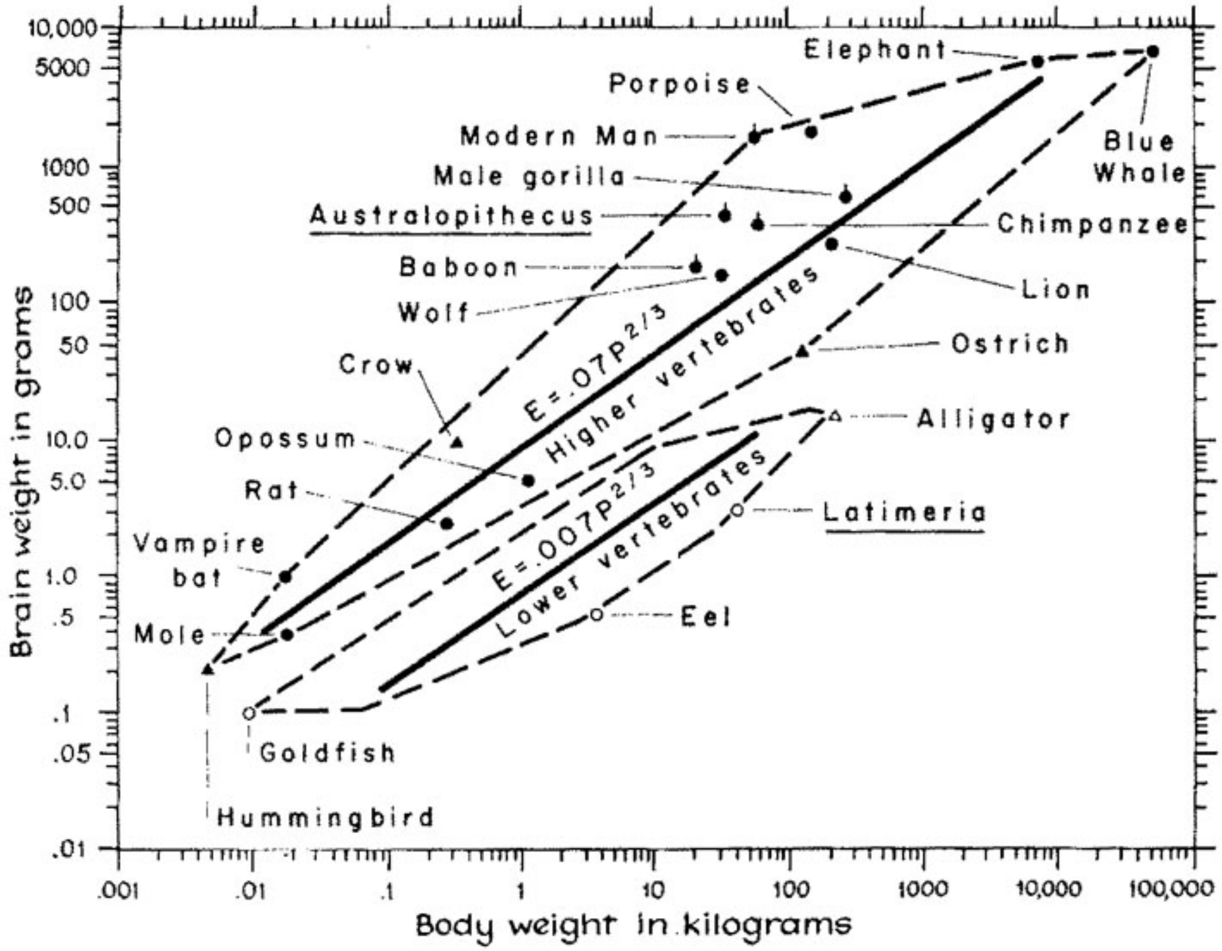
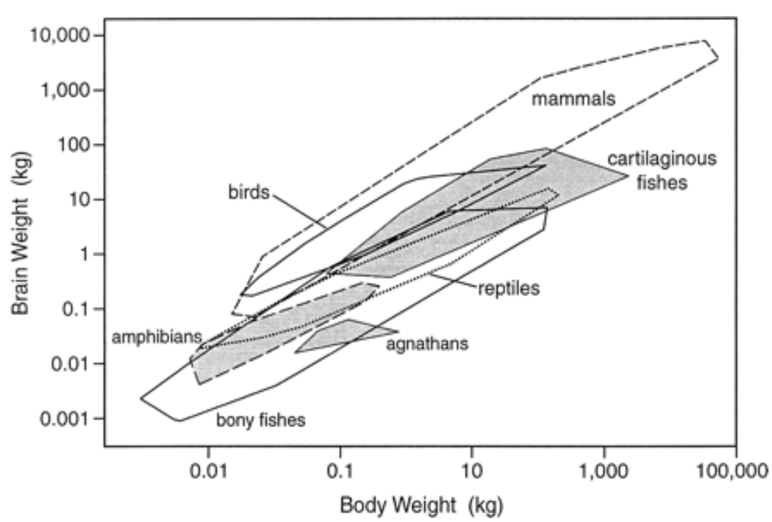
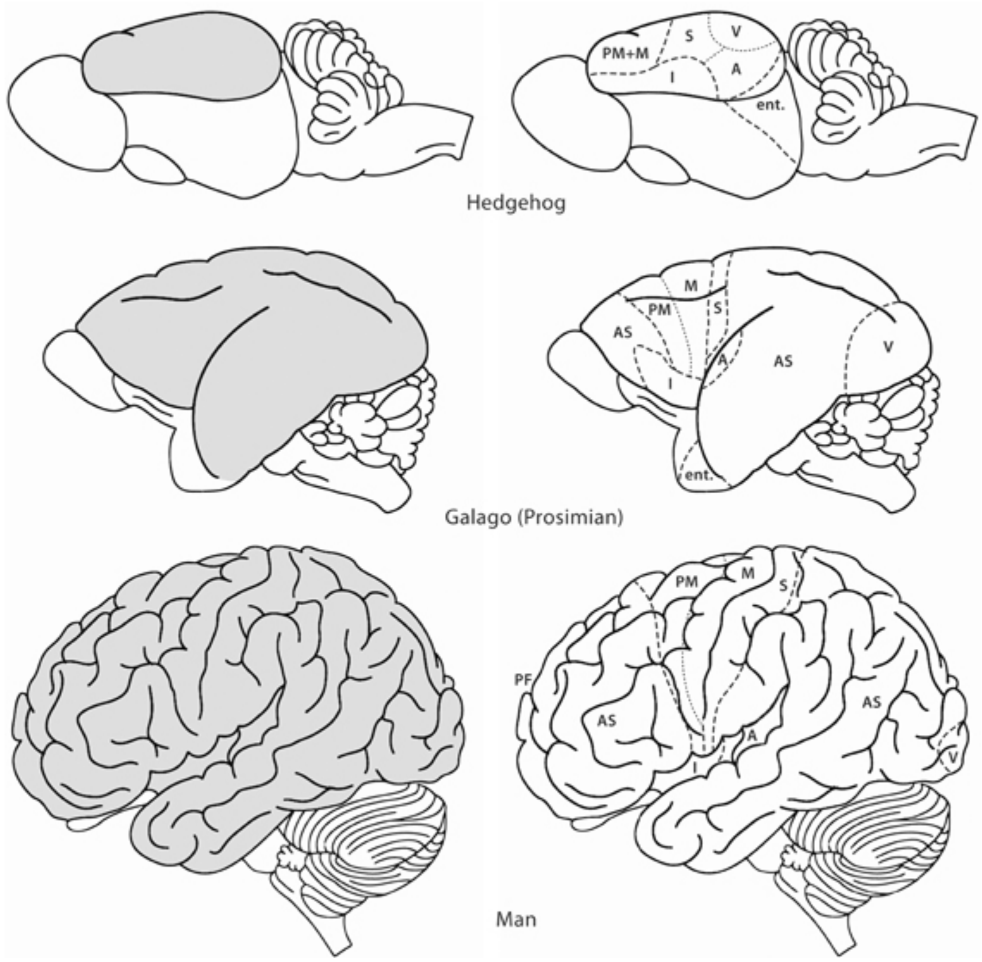


http://neurosciencelibrary.org/evolution/paleo/images/BrnBodwt6.jpg (http://neurosciencelibrary.org/evolution/paleo/images/BrnBodwt6.jpg)



(Northcutt, 2002) (http://doi.org/10.1093/icb/42.4.743)

- Differences in size of the cerebral cortex



(Hofman, 2014) (https://doi.org/10.3389/fnana.2014.00015)

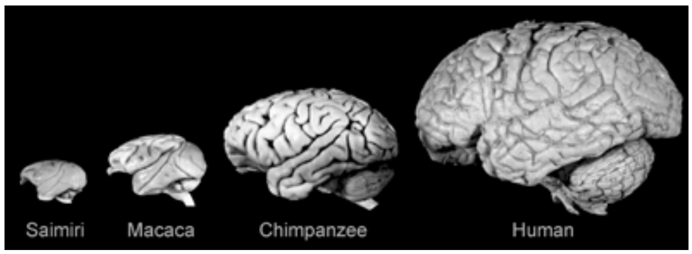
Figure 1. Lateral views of the brains of some mammals to show the evolutionary development of the neocortex (gray). In the hedgehog almost the entire neocortex is occupied by sensory and motor areas. In the prosimian Galago the sensory cortical areas are separated by an area occupied by association cortex (AS). A second area of association cortex is found in front of the motor cortex. In man these anterior and posterior association areas are strongly developed. A, primary auditory cortex; AS, association cortex; Ent, entorhinal cortex; I, insula; M, primary motor cortex; PF, prefrontal cortex; PM, premotor cortex; S, primary somatosensory cortex; V, primary visual cortex. Modified with permission from Nieuwenhuys (1994).

Structural measure	Non-human comparison	Human
Cortical gray matter %/tot brain vol	insectivores 25%	50%

Cortical gray + white	mice 40%	80%
Cerebellar mass	primates, mammals 10-15%	10-15%

- Evidence for greater gray and white matter (relative to total brain volume) in human cerebral cortex

(Rakic, 2009) (http://dx.doi.org/10.1038/nrn2719)



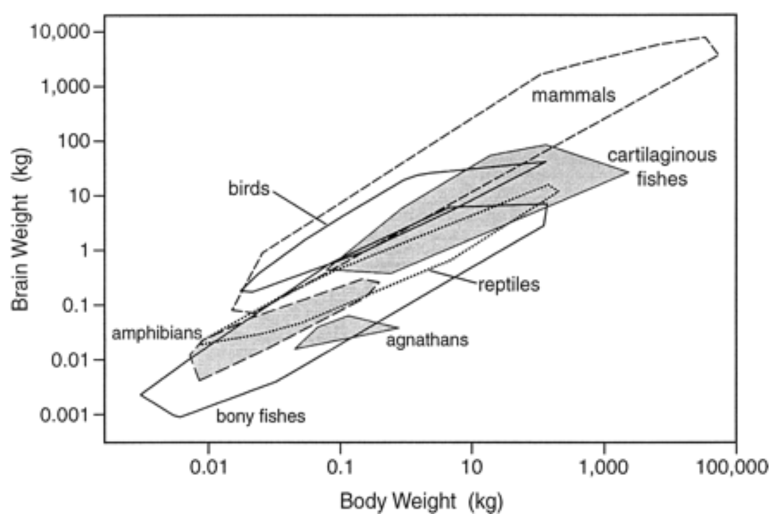
(Hofman, 2014) (https://doi.org/10.3389/fnana.2014.00015)

Take homes

- Brain sizes scale with body size
- Brain sizes (more or less) scale with animal class (more or less)

Old story

- Within mammals, human brains bigger than expected
    - Higher *encephalization quotient* – deviation from species-typical norm

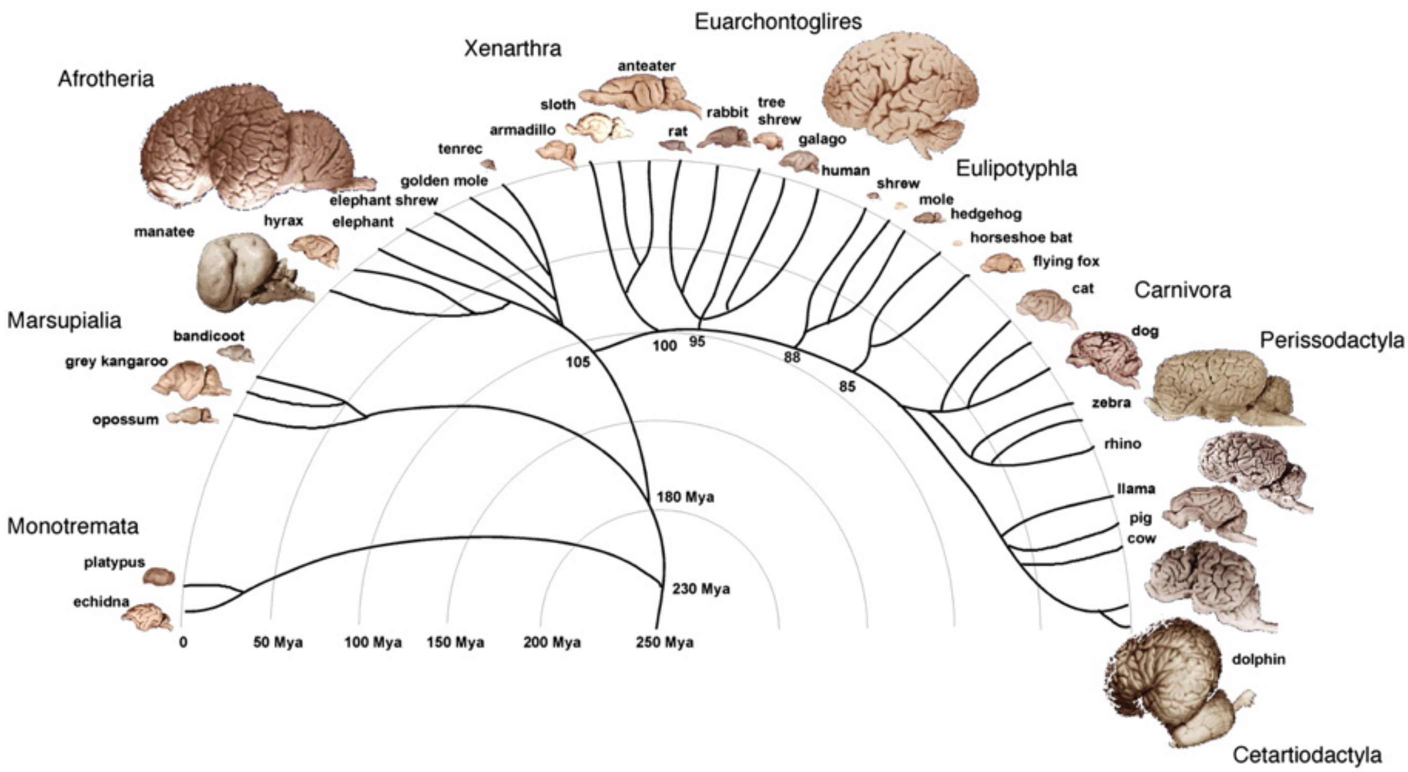


(Northcutt, 2002) (http://doi.org/10.1093/icb/42.4.743)

- Humans have larger cerebral cortical gray + white matter than comparable mammals

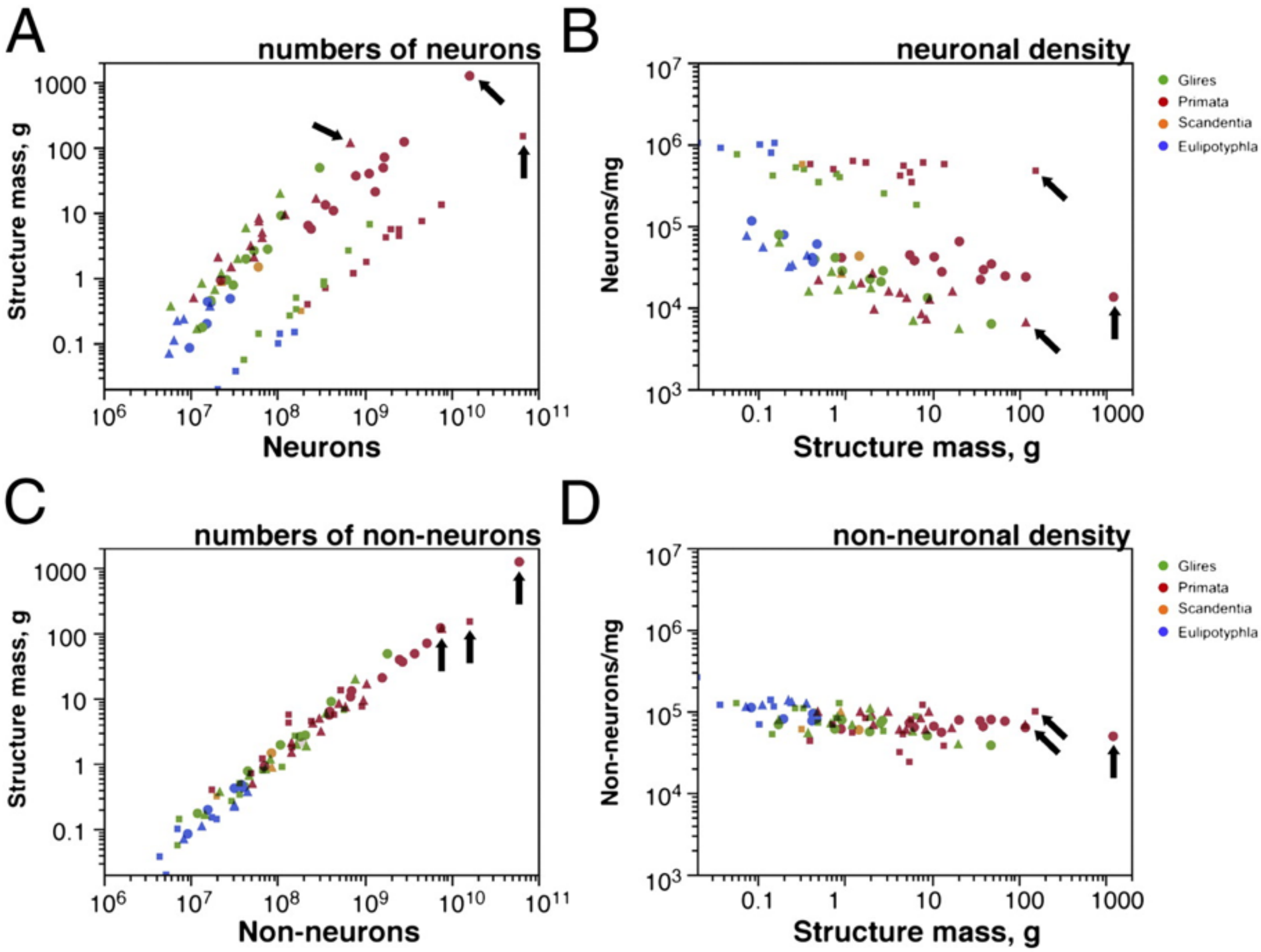
vs. New story

- Does brain size/mass matter (that much)?
- “Size matters” (brain mass) presumes similarity among brains at micro-level
- Big (large mass) brains arise in multiple mammalian lineages



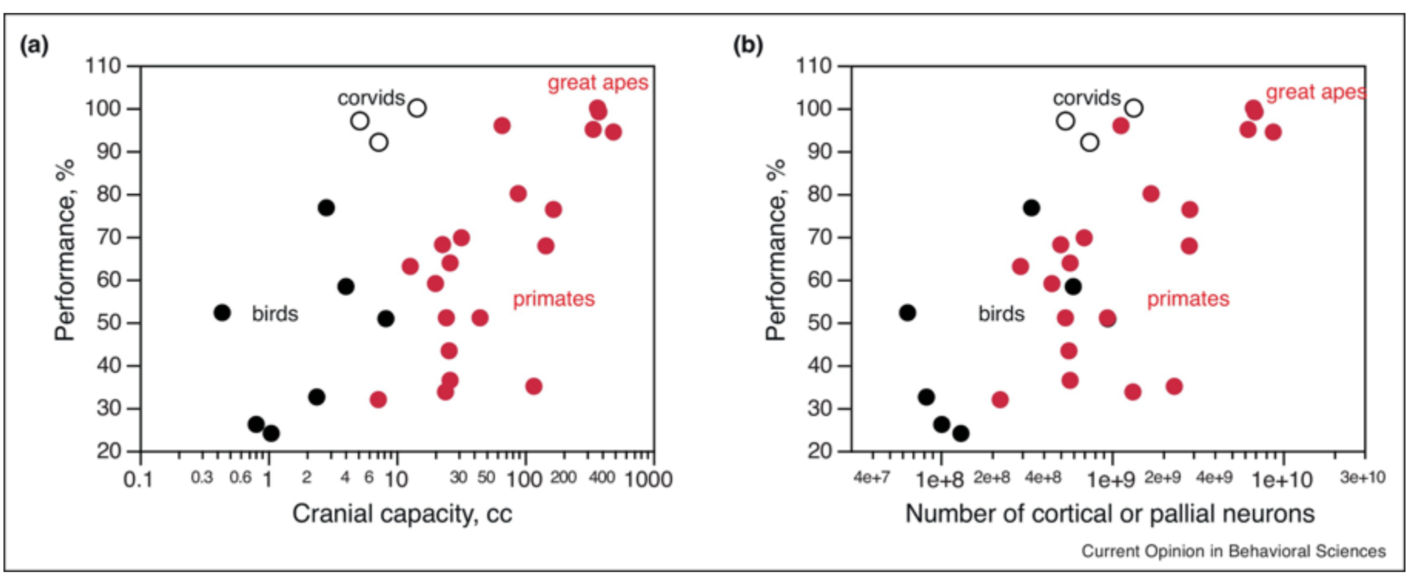
(Herculano-Houzel, 2012) (http://doi.org/10.1073/pnas.1201895109)

- *# of cortical neurons* more important difference than brain mass
- The primate advantage -> more cortical neurons, but not larger neurons & not more neurons in cerebellum
- Human brain just scaled up (non-ape) primate brain



(Herculano-Houzel, 2012) (http://doi.org/10.1073/pnas.1201895109)

of cortical (or in birds, pallidum) neurons predicts “cognition?”

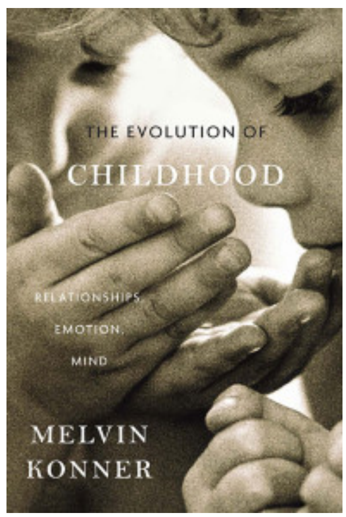


(Herculano-Houzel, 2017) (http://doi.org/10.1016/j.cobeha.2017.02.004)

The Human Advantage (Herculano-Houzel, 2016)

- Brain
  - More neurons in cerebral cortex than other mammals
- Behavior
  - Less time spent foraging
    - Higher quality/more energetically dense food
    - Higher food availability
  - Cultural factors (agriculture + cooking), see also (Wrangham, 2009)

A further human advantage



Human brain development

Prenatal period

Insemination

- 3-4 days before or up to 1-2 days after…
  - Ovulation

Fertilization

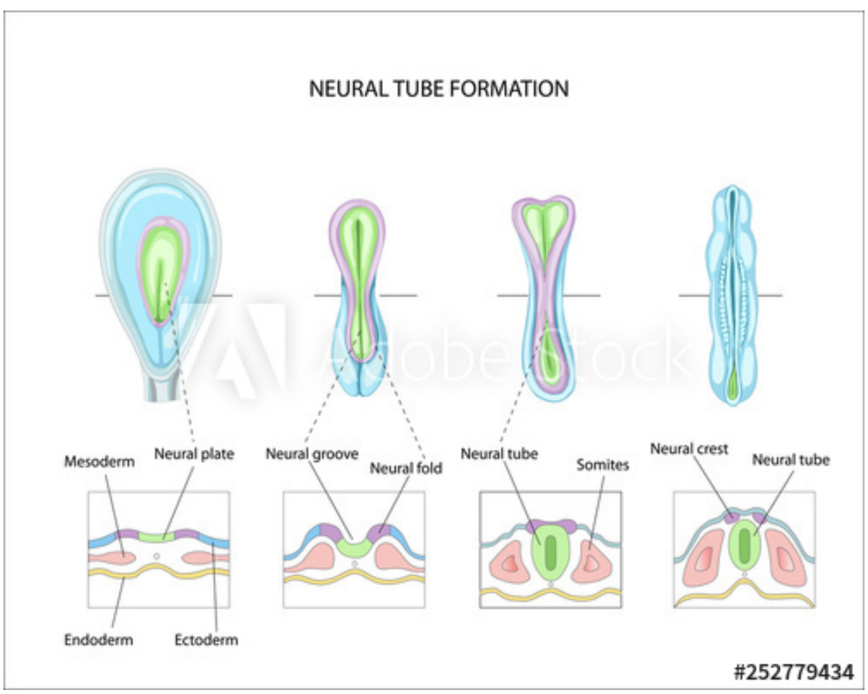
- Within ~ 24 hrs of ovulation

Implantation

- ~ 6 days after fertilization

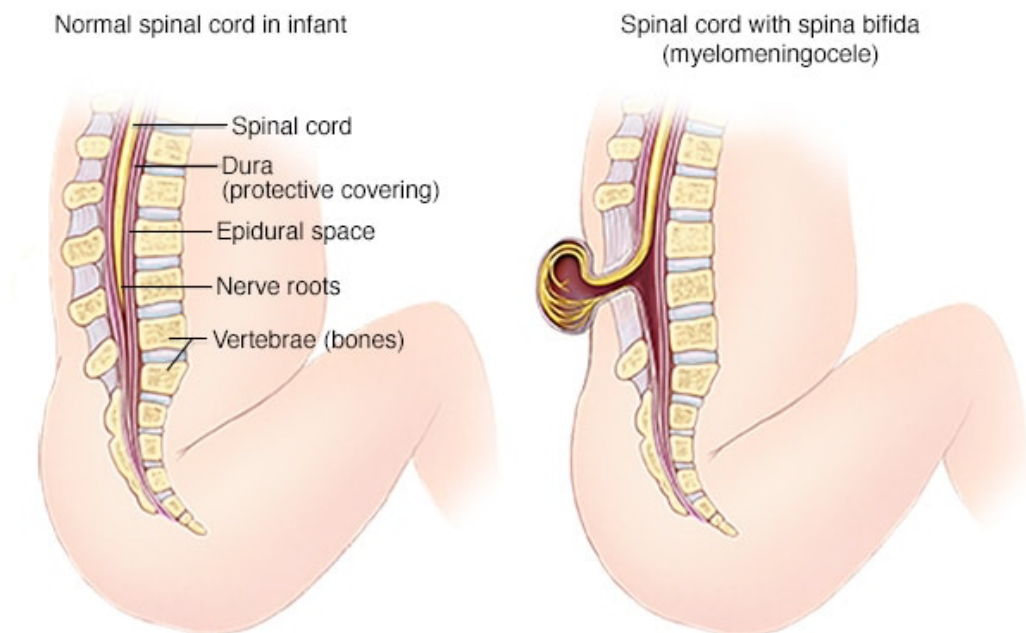
Early embryogenesis

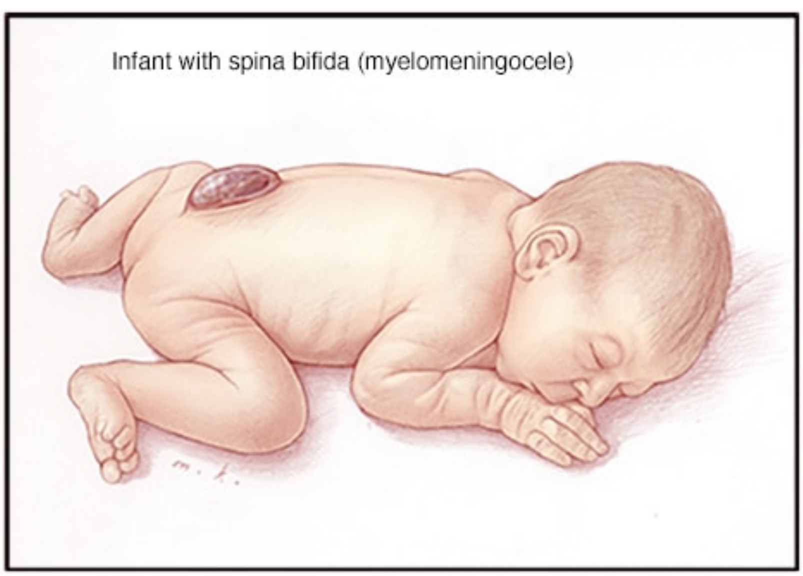
Formation of *neural tube* (neurulation)



- Embryonic layers: ectoderm, mesoderm, endoderm

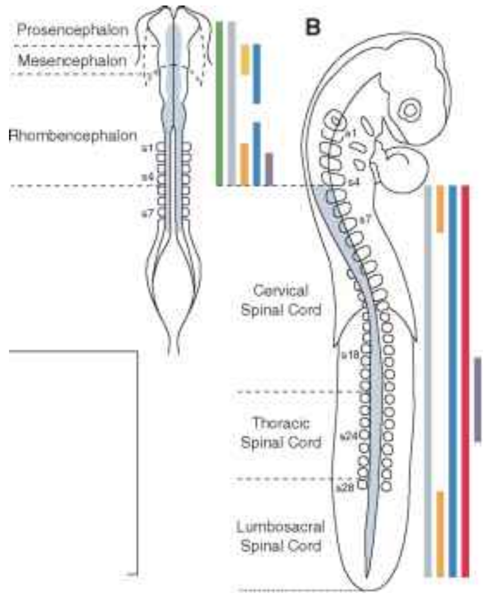
- ~18-26 days
- Failures of neural tube closure
  - Anencephaly (rostral neuraxis)
  - Spina bifida (caudal neuraxis)





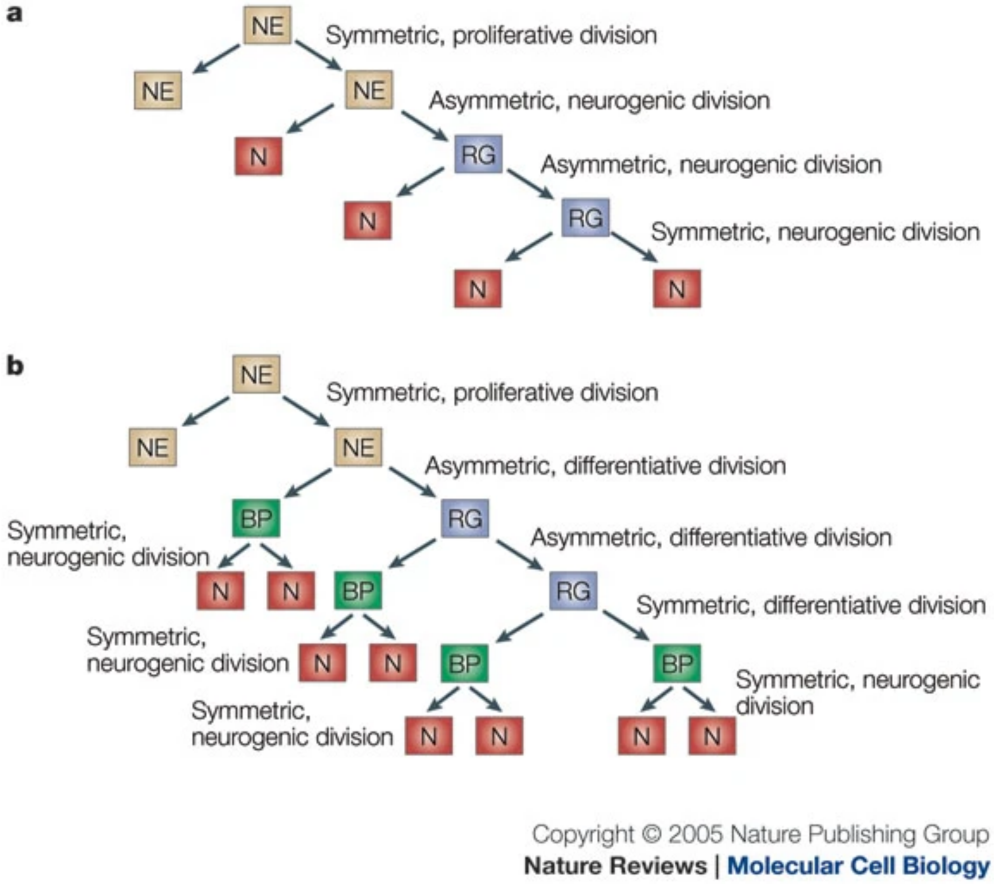
https://www.mayoclinic.org/diseases-conditions/spina-bifida/symptoms-causes/syc-20377860 (https://www.mayoclinic.org/diseases-conditions/spina-bifida/symptoms-causes/syc-20377860)

- Neural tube becomes
  - Ventricles & cerebral aqueduct
  - Central canal of spinal cord



Neurogenesis and gliogenesis

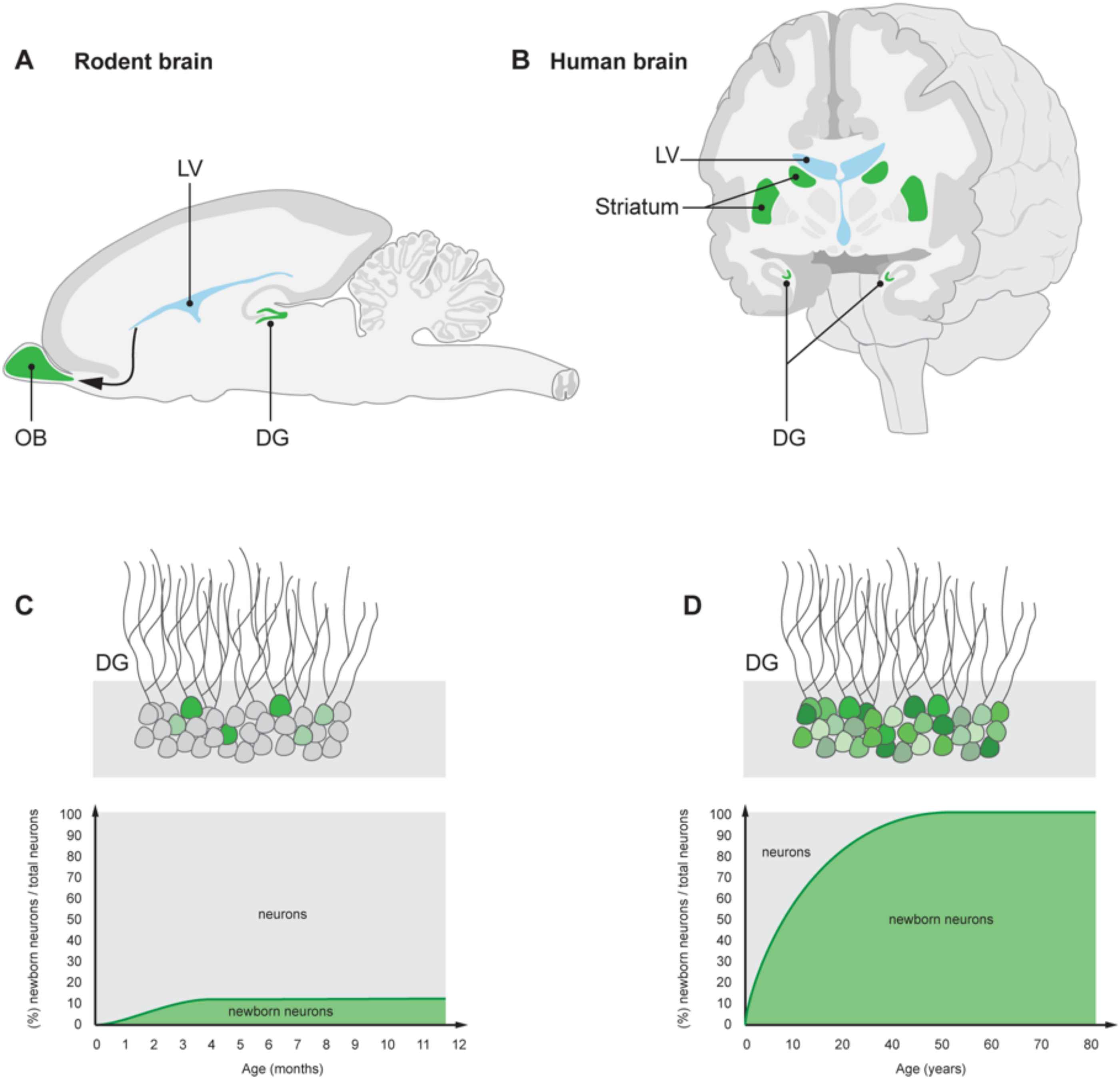
- Neuroepithelium cell layer lines neural tube
  - Peri-ventricular regions remain home to cells that can produce new cells



(Götz & Huttner, 2005) (https://doi.org/10.1038/nrm1739)

> The lineage trees shown provide a simplified view of the relationship between neuroepithelial cells (NE), radial glial cells (RG) and neurons (N), without (a) and with (b) basal progenitors (BP) as cellular intermediates in the generation of neurons. They also show the types of cell division involved.
>
> (Götz & Huttner, 2005) (https://doi.org/10.1038/nrm1739)

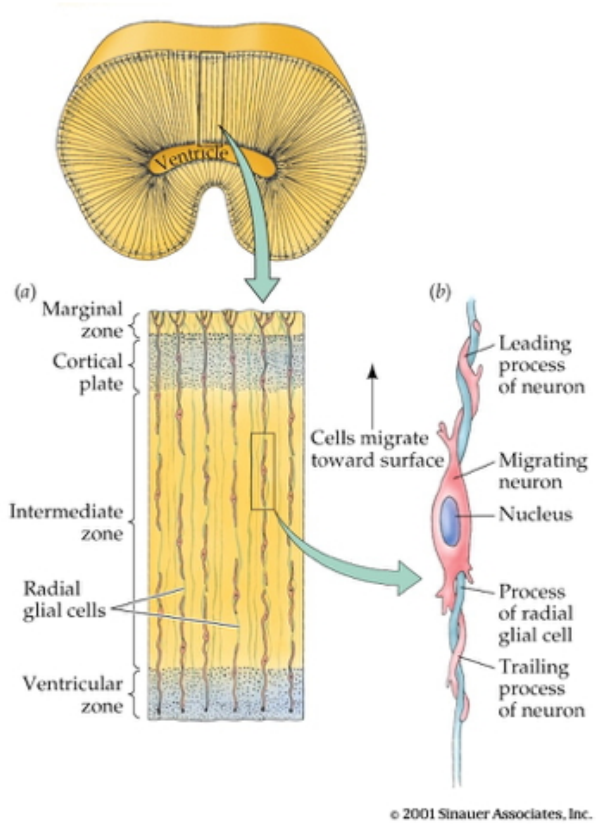
- Areas in adult human brain that generate new neurons
  - hippocampus
  - striatum
  - olfactory bulb (minimally)
  - weak evidence for neurogenesis in adult cerebral cortex

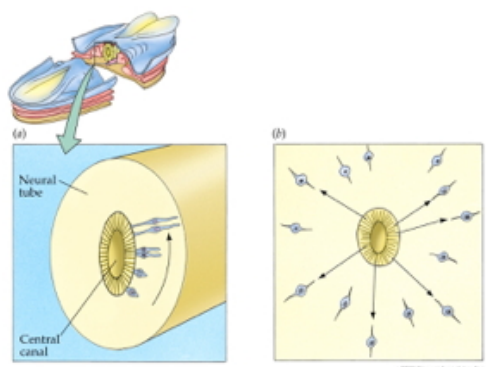


Ernst & Frisen 2015 (https://doi.org/10.1371/journal.pbio.1002045)

- Neural stem cells
  - Undergo *symmetric* & *asymmetric* cell division
  - Generate glia, neurons, and basal progenitor cells

Radial glia and cell migration





Radial unit hypothesis

(Rakic, 2009) (http://dx.doi.org/10.1038/nrn2719)

Neuron Migration

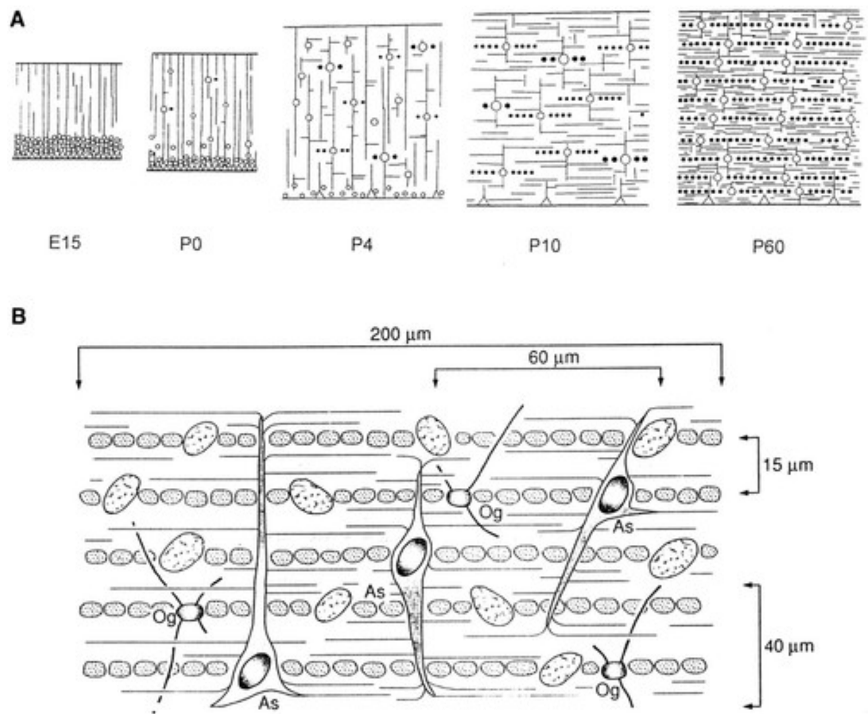
Neuronal Migration

Axon growth cone

Growth cone filopodia

- Chemoattractants
  - e.g., Nerve Growth Factor (NGF)
- Chemorepellents
- Receptors in growth cone detect chemical gradients

Glia migrate, too



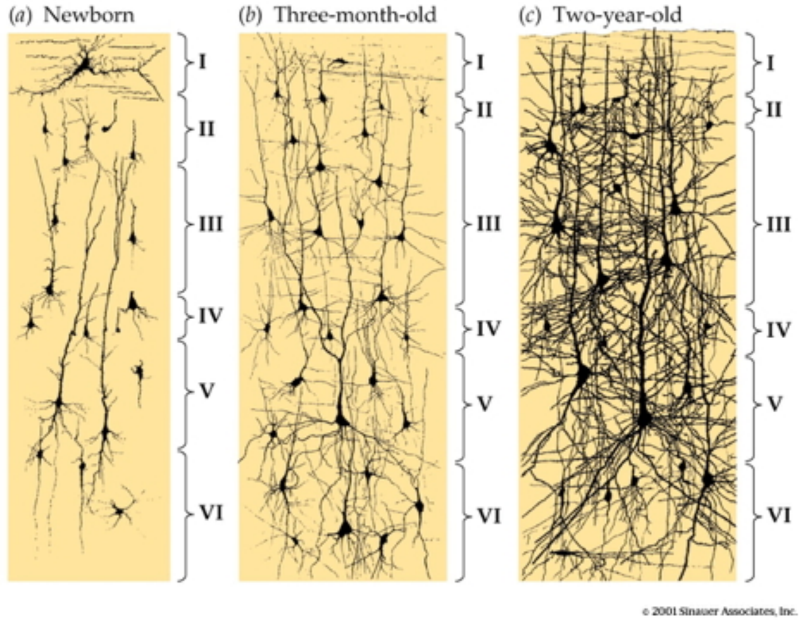
(Baumann & Pham-Dinh, 2001) (http://dx.doi.org/10.1152/physrev.2001.81.2.871)

Differentiation

- Neuron vs. glial cell
- Cell type
  - myelin-producing vs. astrocyte vs. microglia
  - pyramidal cell vs. stellate vs. Purkinje vs. …
- NTs released
- Where to connect

Infancy & Early Childhood

Synaptogenesis

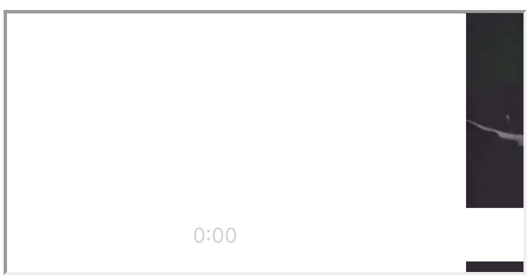


Proliferation, pruning

- Early proliferation
- Later pruning
- Rates, peaks differ by area

Apoptosis

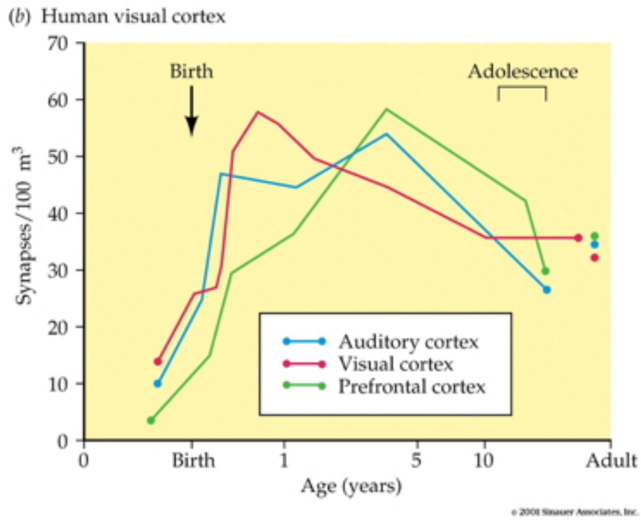
- Programmed cell death



- 20-80%, varies by area
- Spinal cord >> cortex
- Quantity of nerve growth factors (NGF) influences

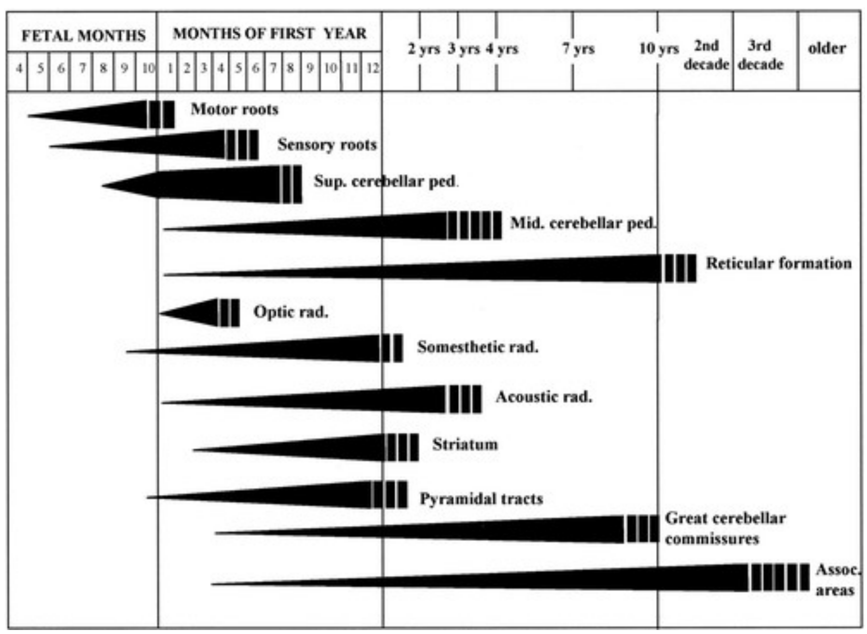
(Rakic, 2009) (http://dx.doi.org/10.1038/nrn2719)

Synaptic rearrangement



- Progressive phase: growth rate >> loss rate
- Regressive phase: growth rate << loss rate

Myelination

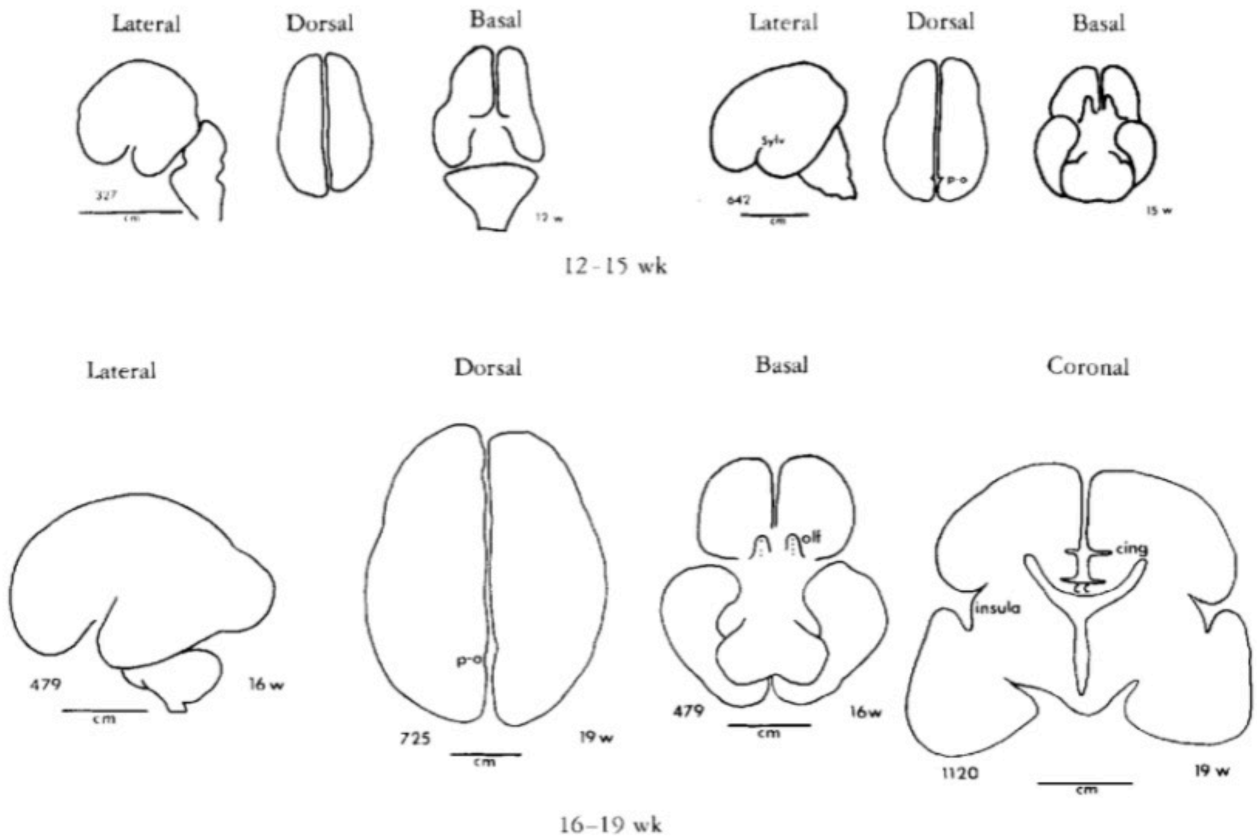


(Baumann & Pham-Dinh, 2001) (http://dx.doi.org/10.1152/physrev.2001.81.2.871)

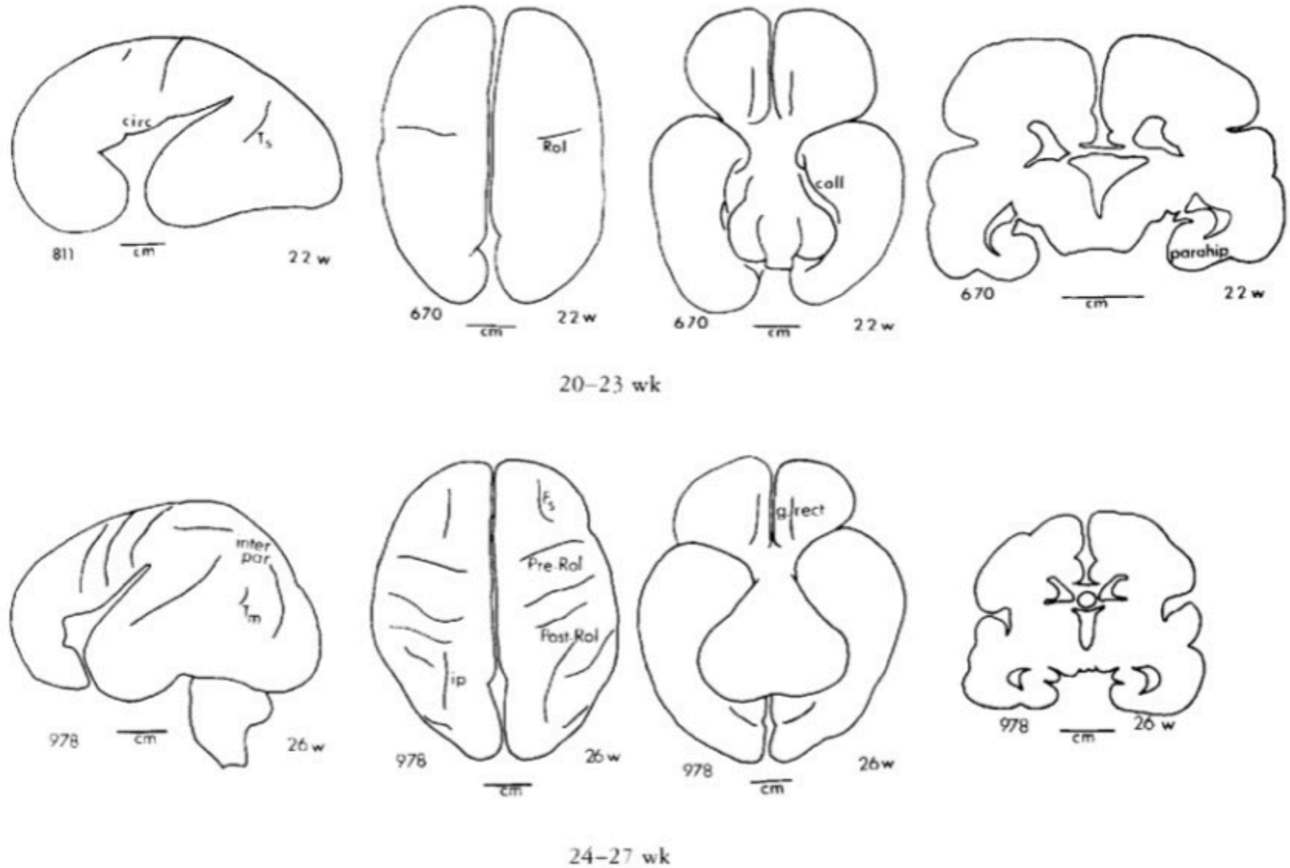
- Neonatal brain largely unmyelinated
- Gradual myelination, peaks in mid-20s
- Non-uniform pattern
  - Spinal cord before brain

- Sensory before motor

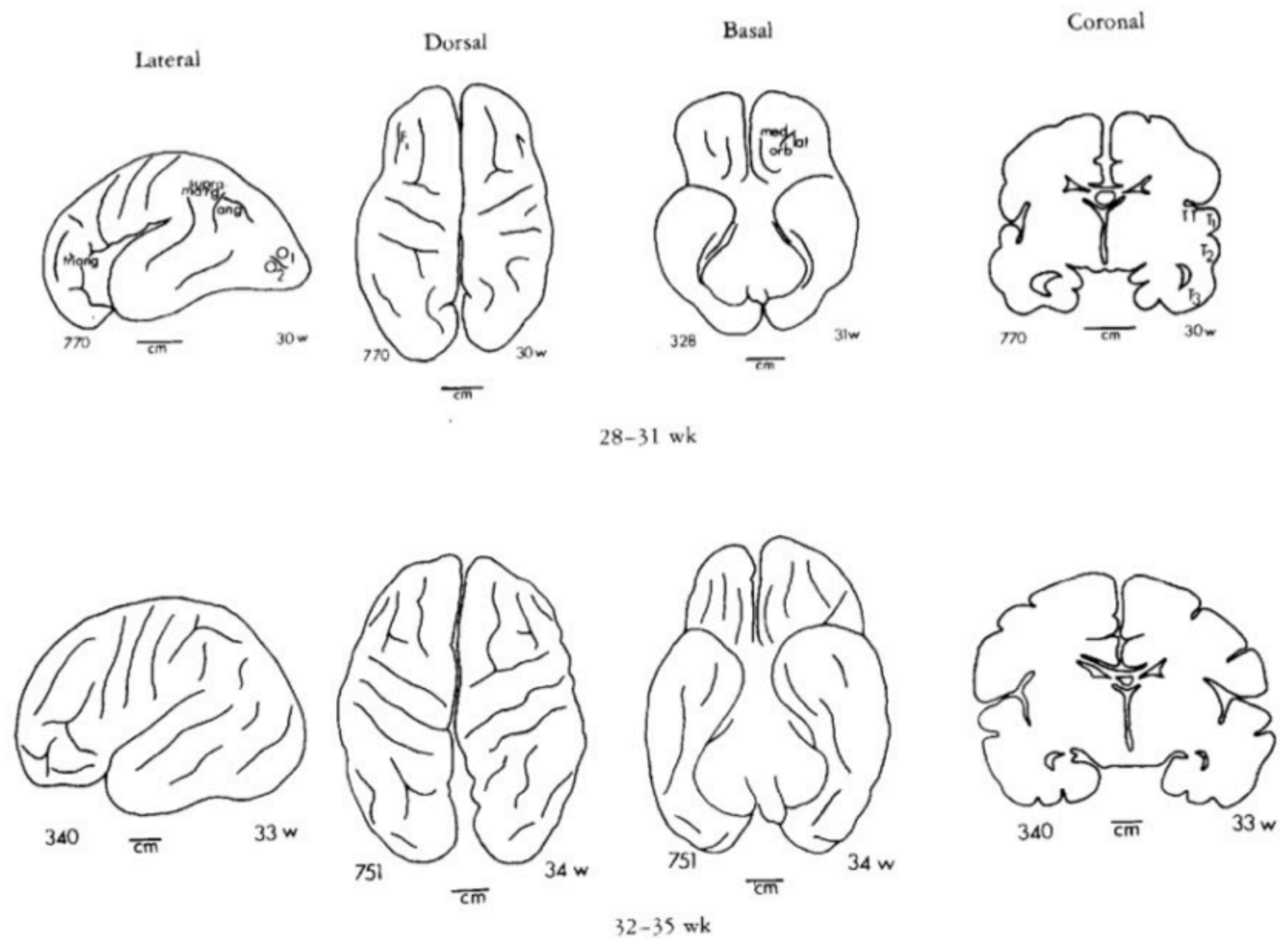
Gyral development



(Chi, Dooling, & Gilles, 1977) (http://doi.org/10.1002/ana.410010109)



(Chi, Dooling, & Gilles, 1977) (http://doi.org/10.1002/ana.410010109)



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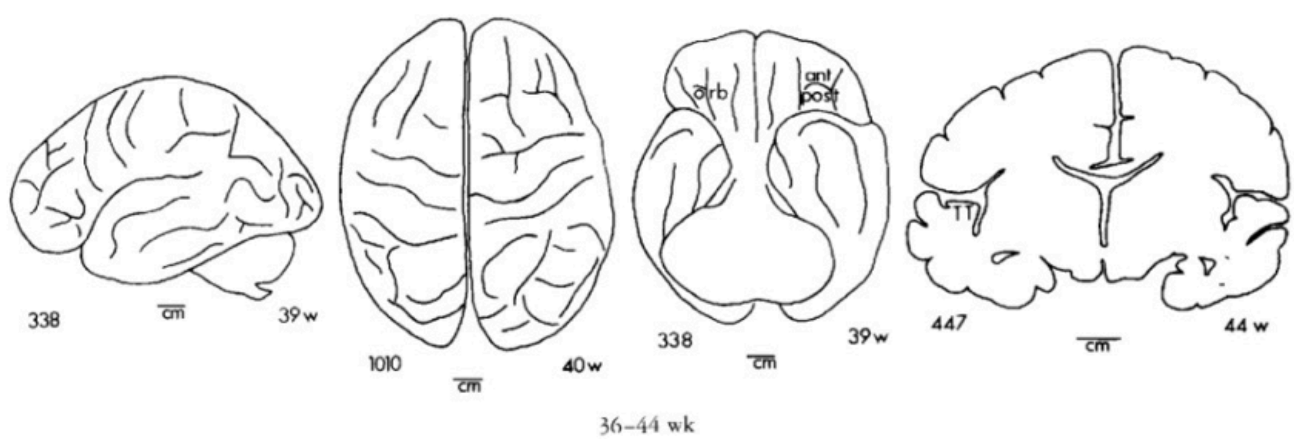
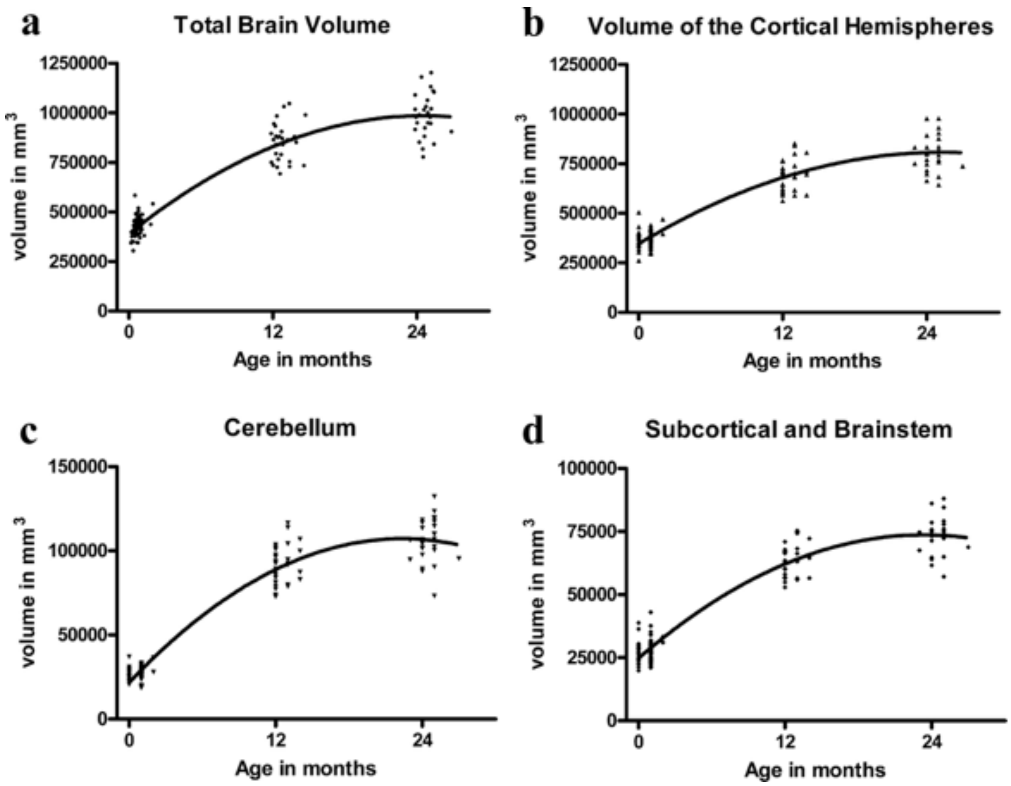


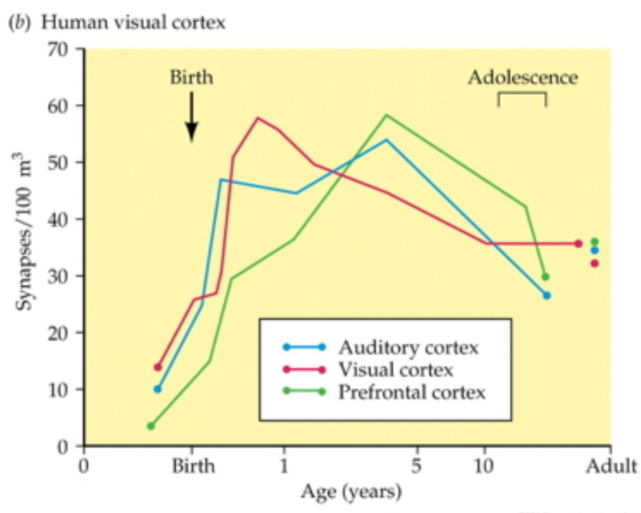
(Chi, Dooling, & Gilles, 1977) (http://doi.org/10.1002/ana.410010109)

Structural/morphometric development

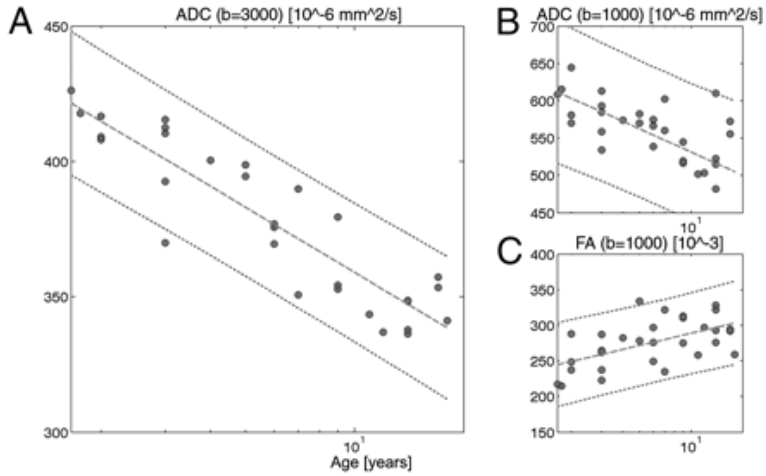


(Knickmeyer et al., 2008) (http://doi.org/10.1523/JNEUROSCI.3479-08.2008)

Synaptogenesis

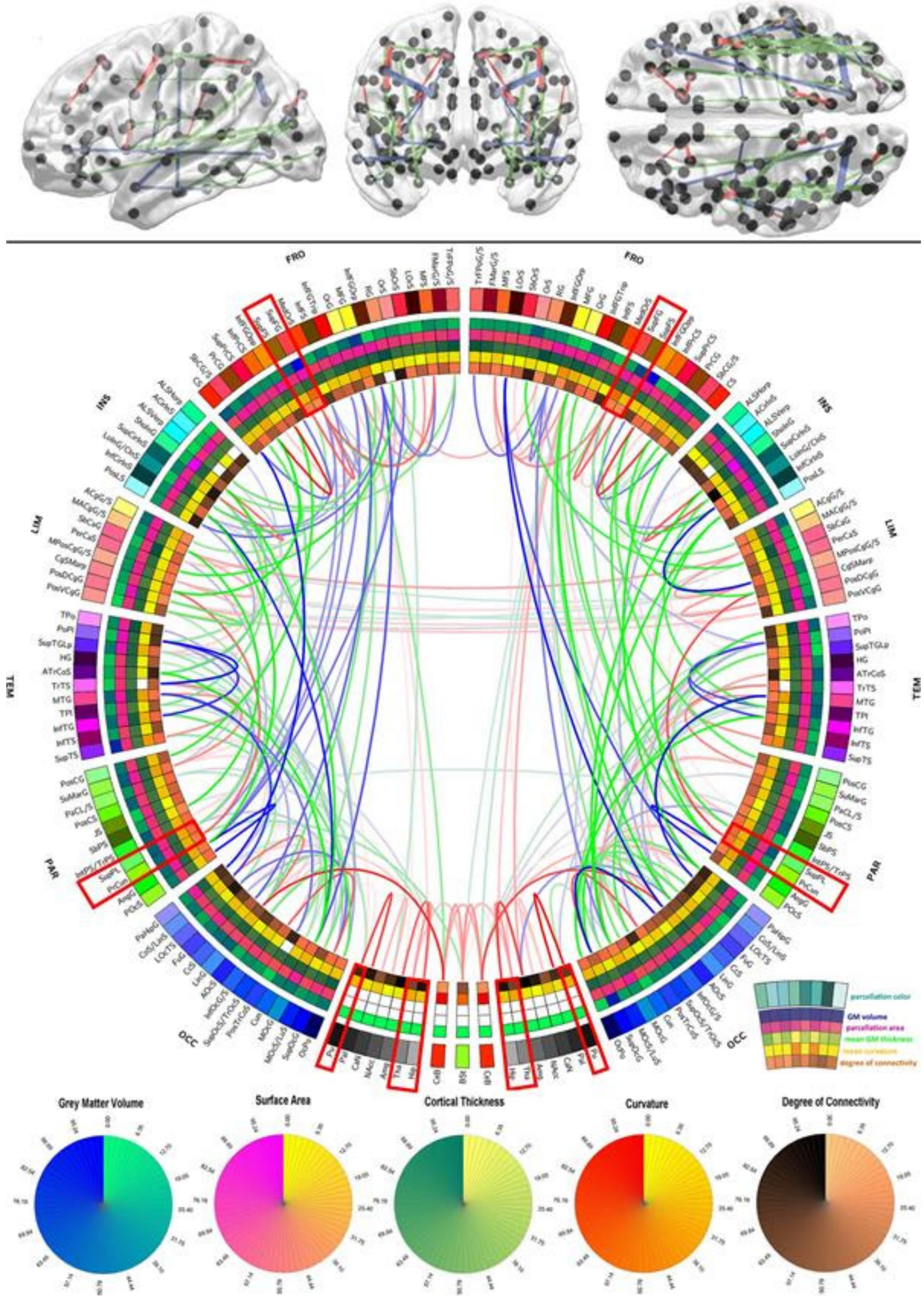


Myelination across human development



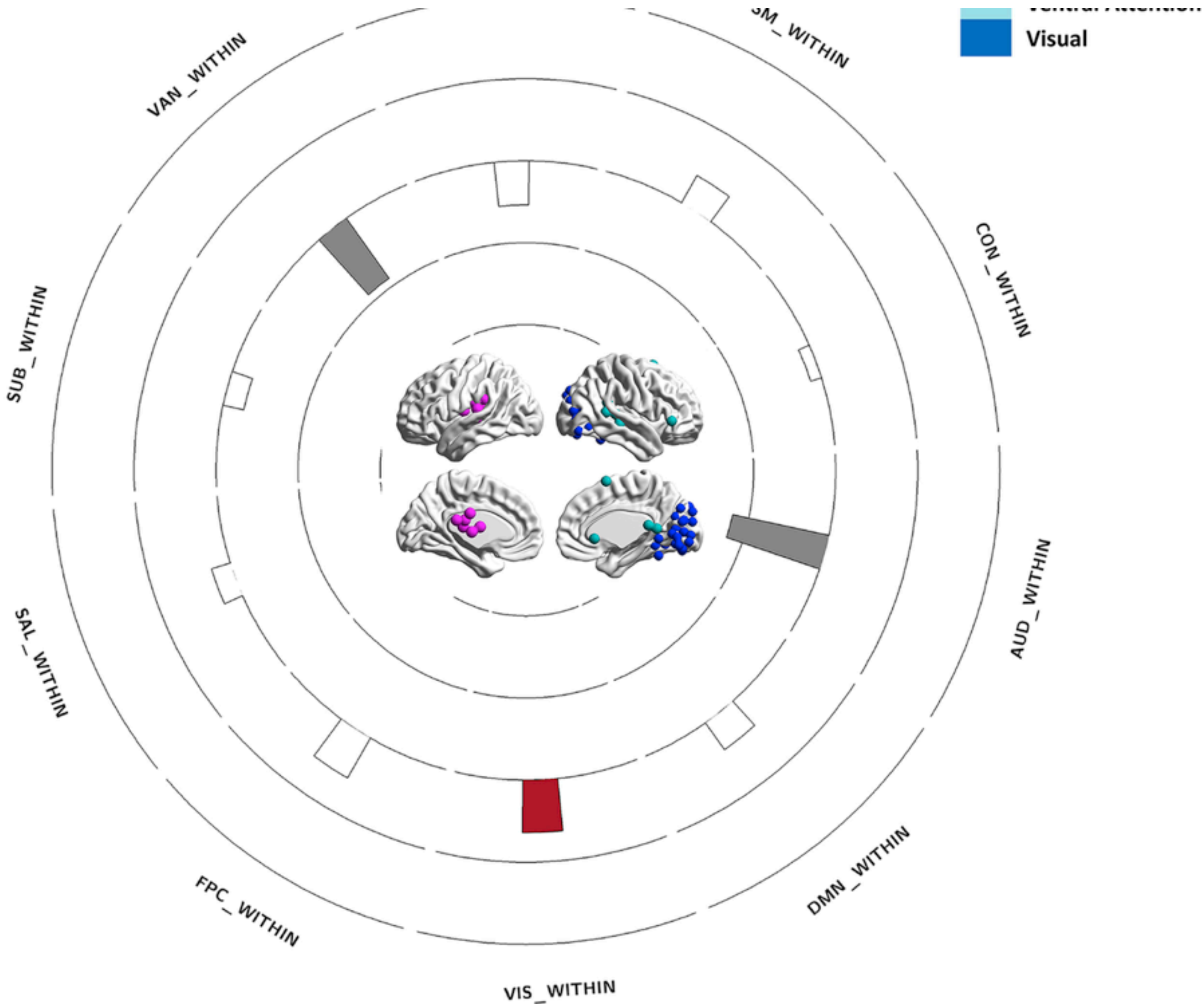
(Hagmann et al., 2010) (http://doi.org/10.1073/pnas.1009073107)

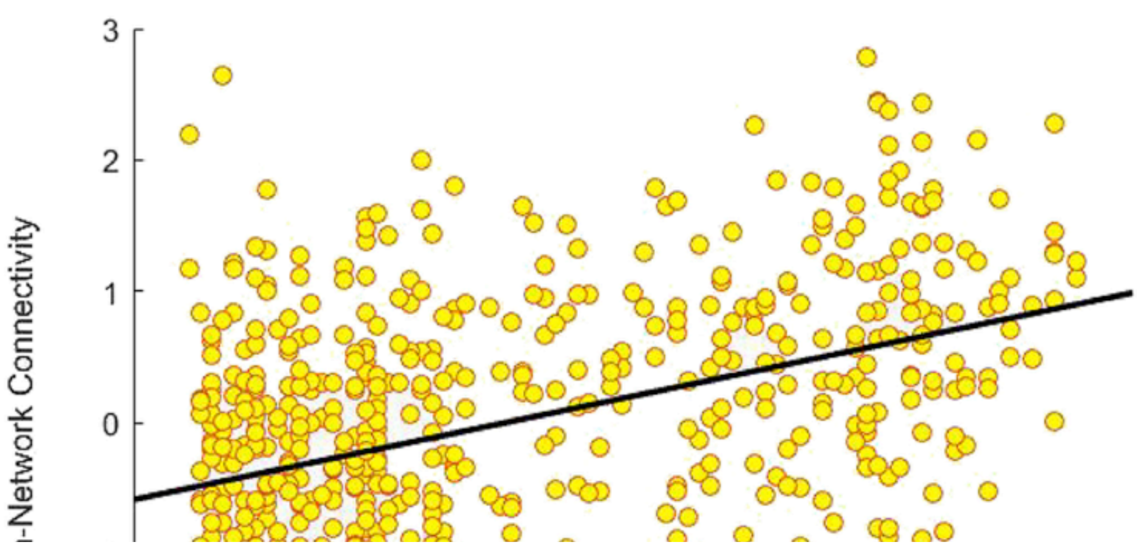
Networks in the brain

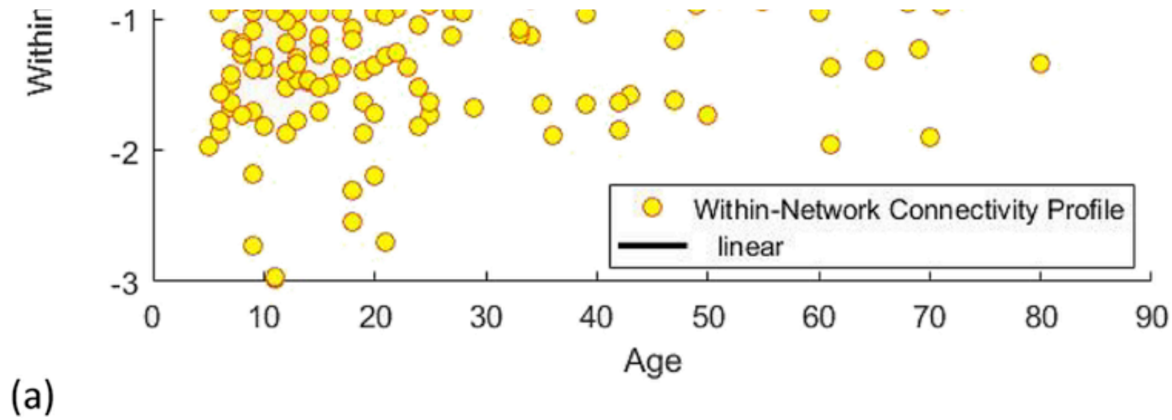


(Irimia & Van Horn, 2014) (http://doi.org/10.3389/fnhum.2014.00051)

- Age-related functional connectivity increases within visual-related areas (Petrican, Taylor, & Grady, 2017) (http://doi.org/10.1016/j.neuroimage.2017.09.025)

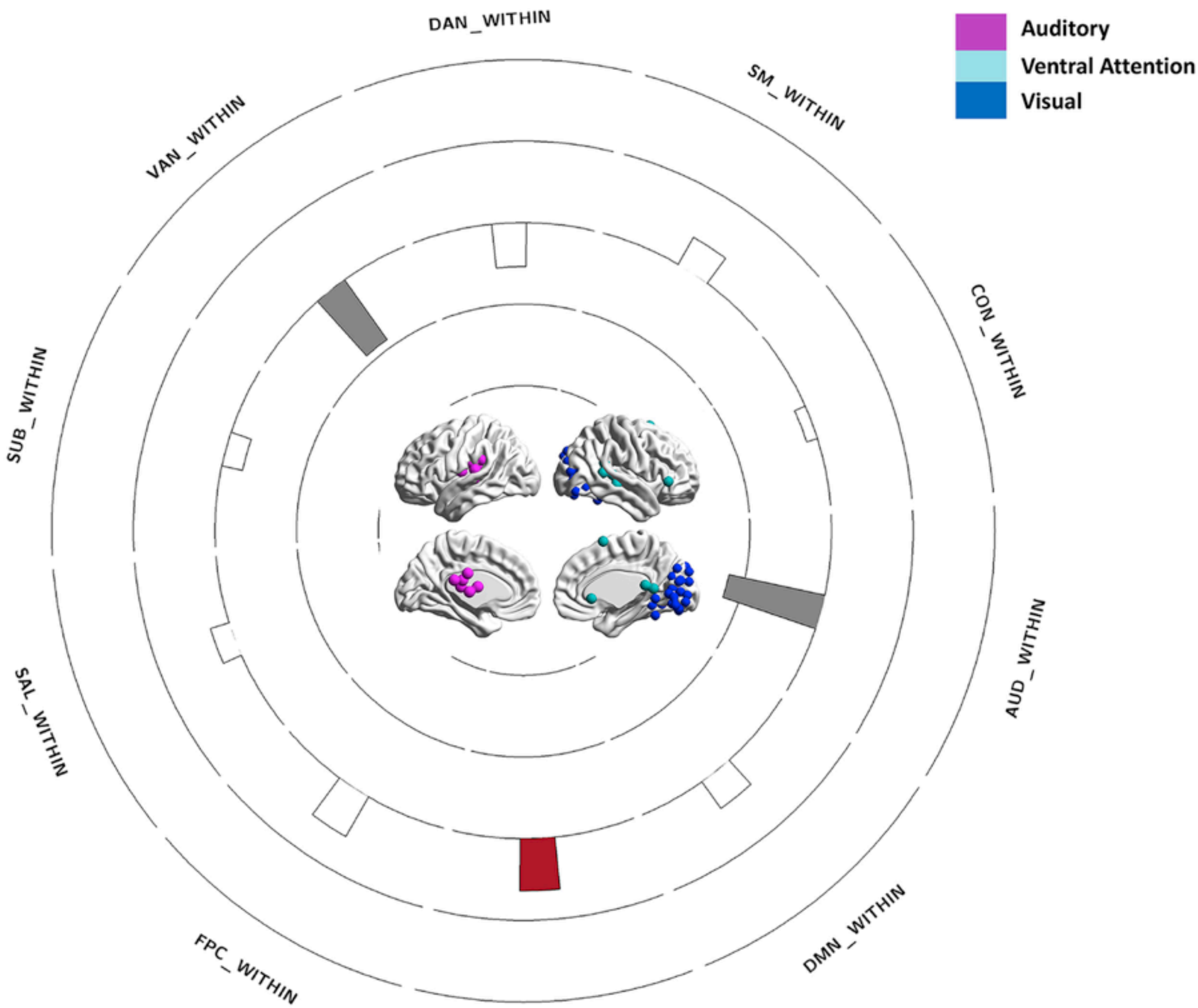

Visual
SM_WITHIN
VAN_WITHIN
CON_WITHIN
SUB_WITHIN
AUD_WITHIN
SAL_WITHIN
FPC_WITHIN
DMN_WITHIN
VIS_WITHIN

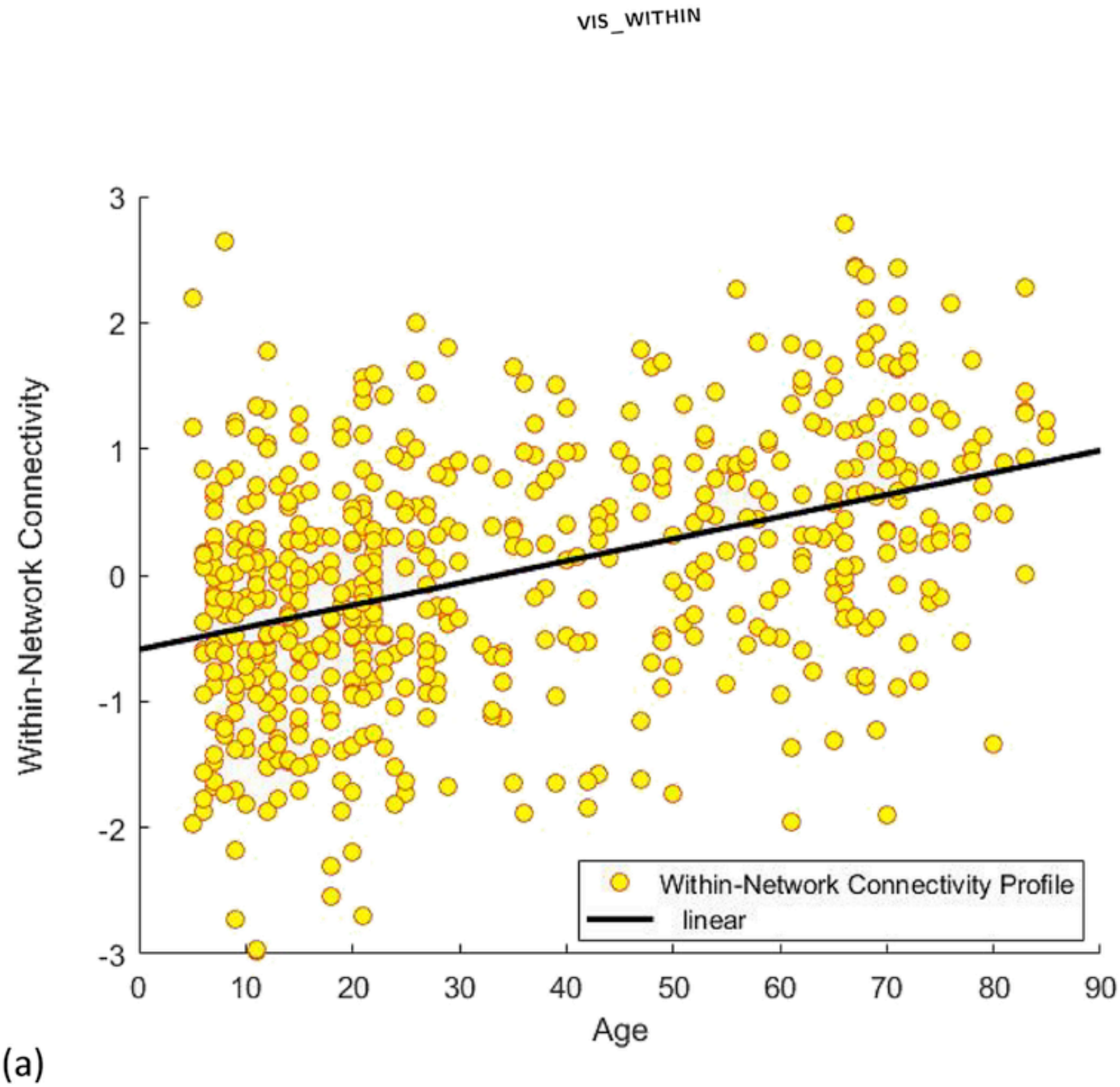

3
2
1
0
-Network Connectivity



(Petrican, Taylor, & Grady, 2017)
(http://doi.org/10.1016/j.neuroimage.2017.09.025)

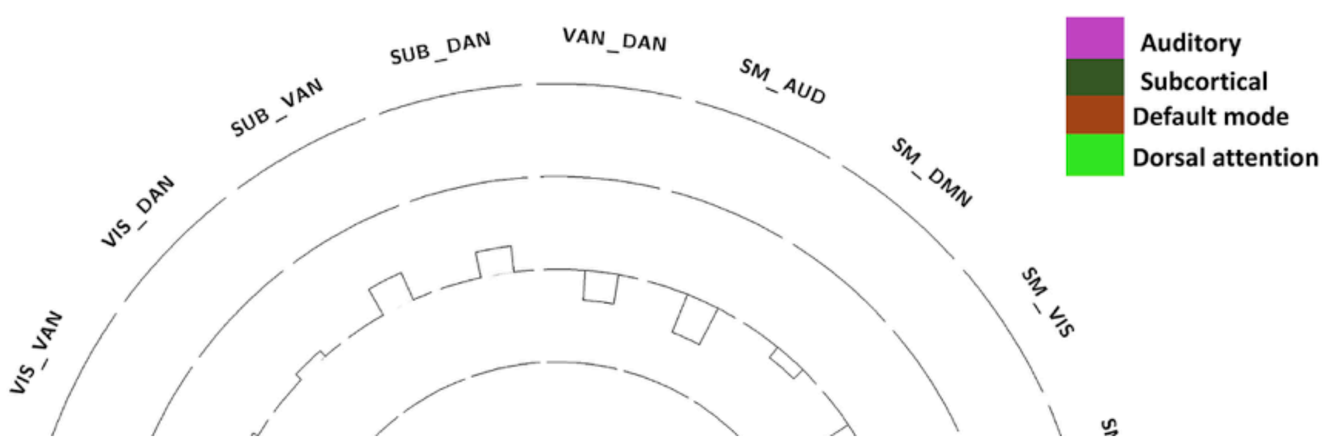
"Control" networks

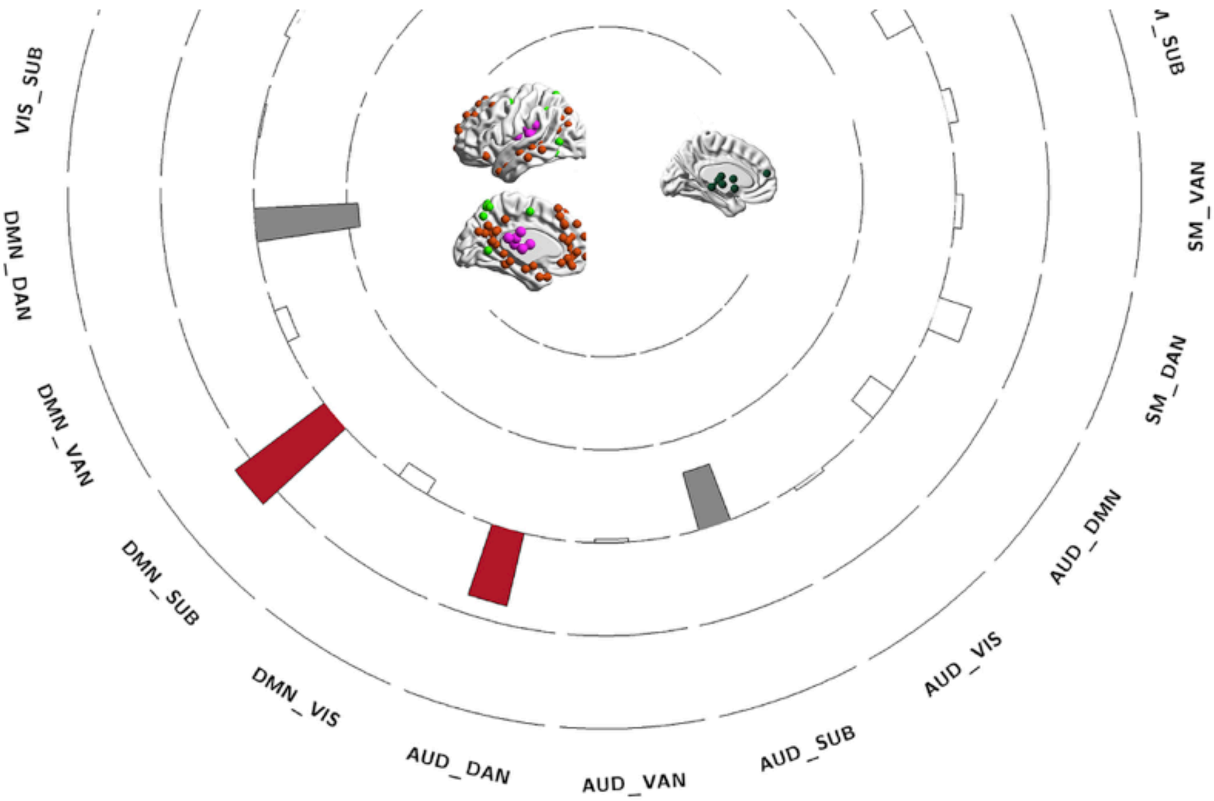


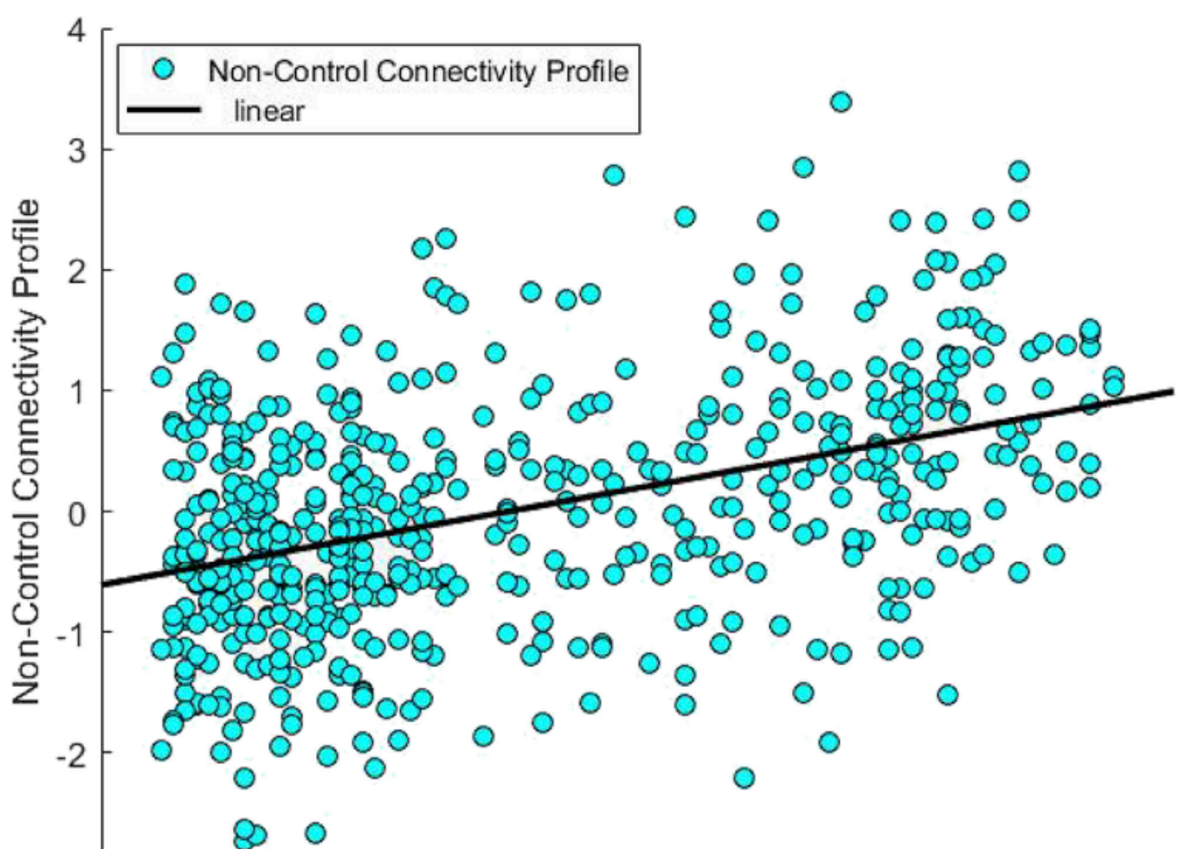


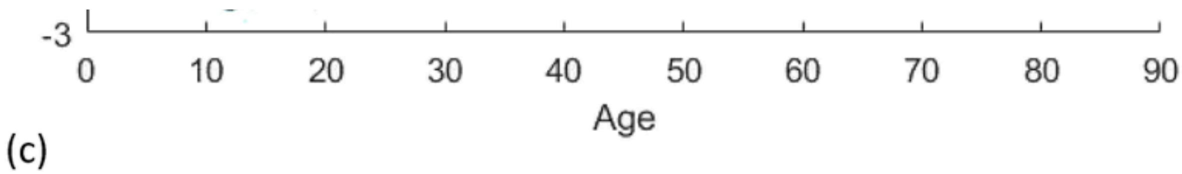
(Petrican, Taylor, & Grady, 2017) (http://doi.org/10.1016/j.neuroimage.2017.09.025)

non-“control” networks



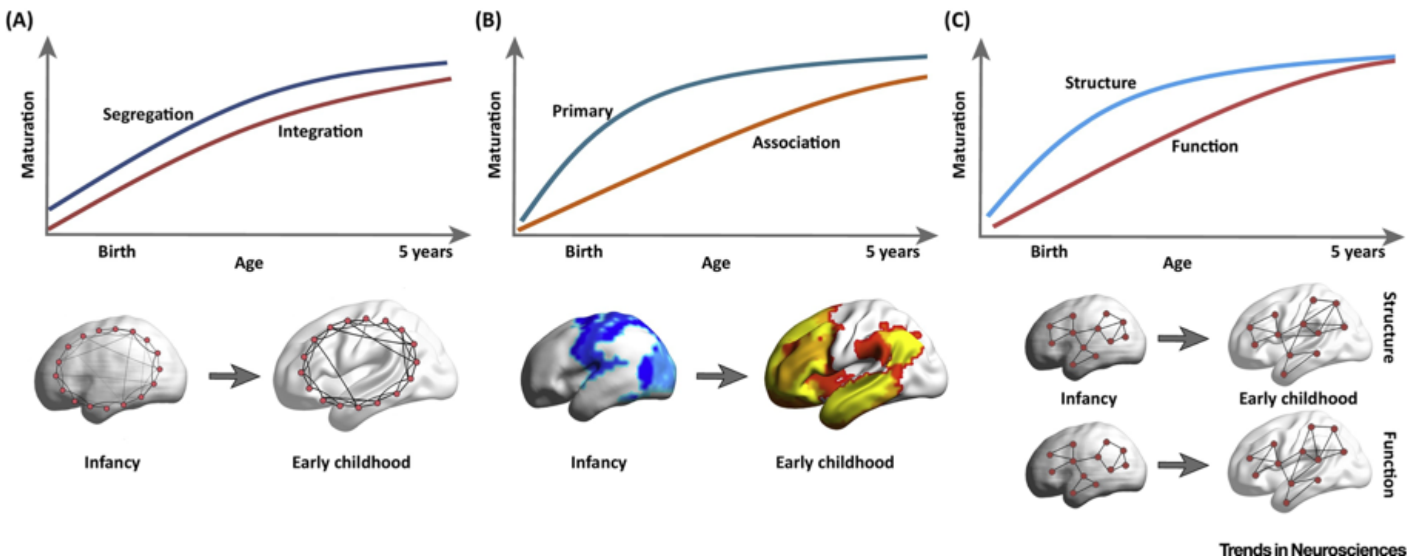

VIS_SUB
DMN_DAN
DMN_VAN
DMN_SUB
DMN_VIS
AUD_DAN
AUD_VAN
AUD_SUB
AUD_VIS
AUD_DMN
SM_DAN
SM_VAN
SUB


Non-Control Connectivity Profile
linear
Non-Control Connectivity Profile
4
3
2
1
0
-1
-2



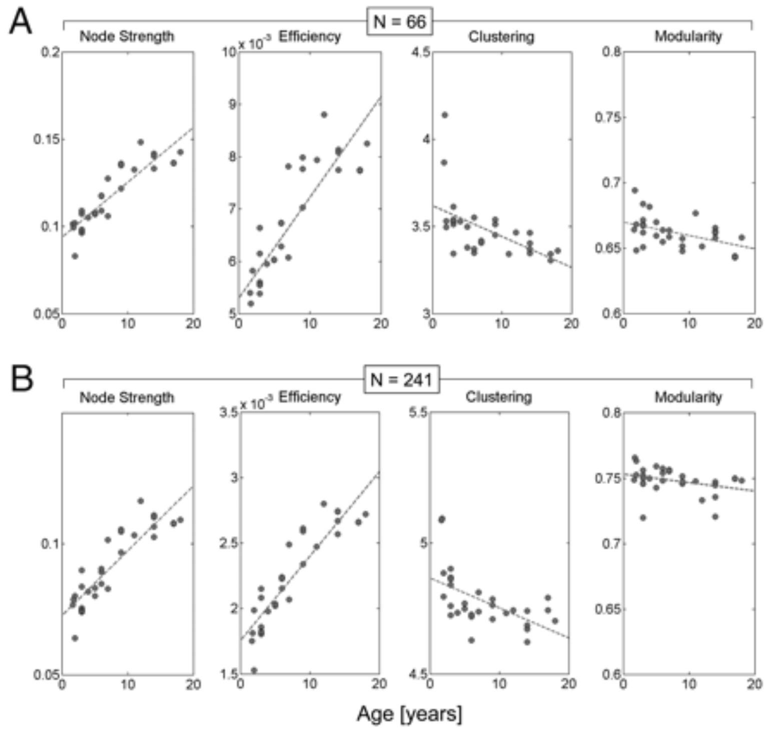
(Petrican, Taylor, & Grady, 2017) (http://doi.org/10.1016/j.neuroimage.2017.09.025)

The “development” of developmental connectomics



(Cao, Huang, & He, 2017) (http://doi.org/10.1016/j.tins.2017.06.003)

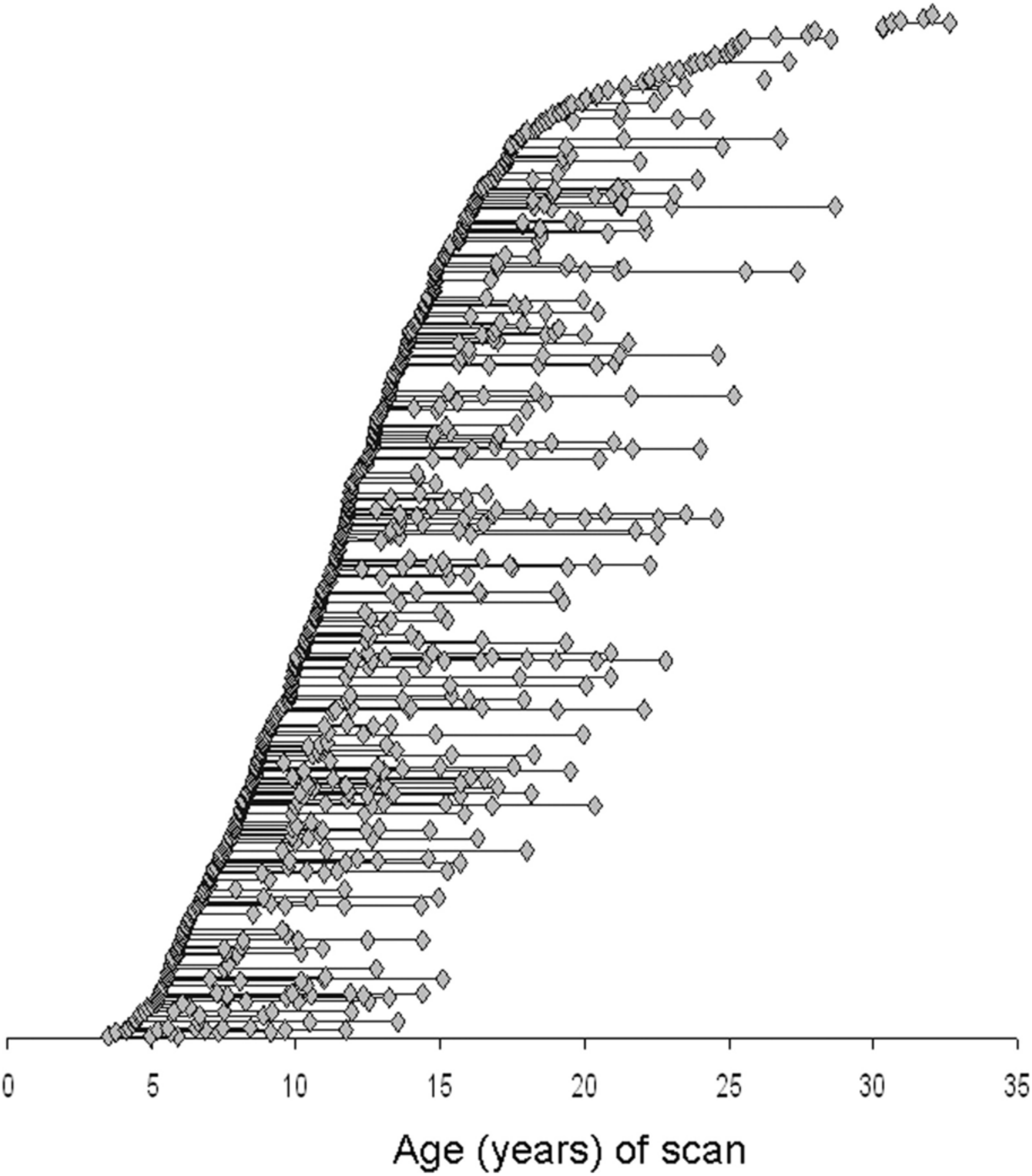
Myelination changes “network” properties



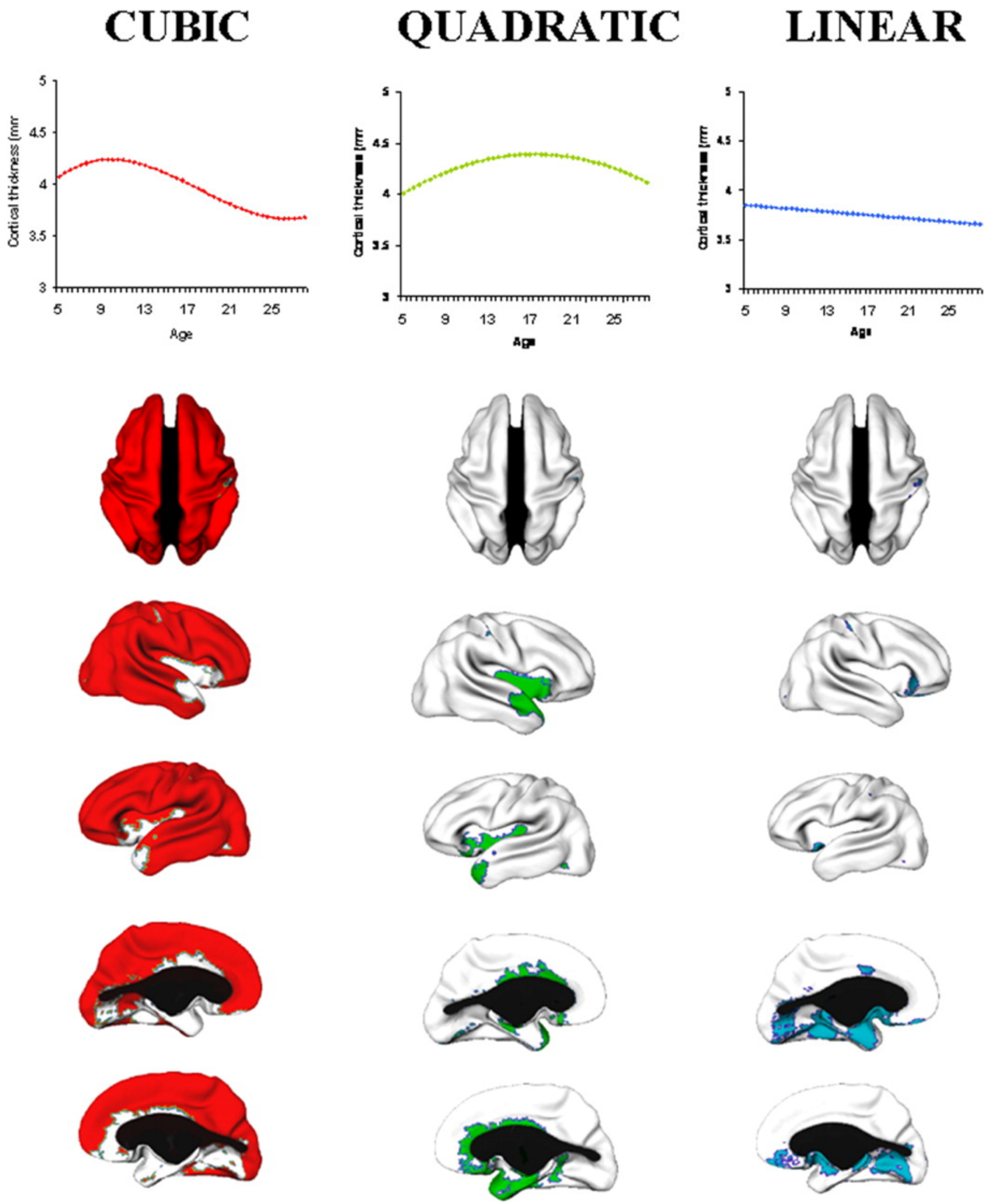
(Hagmann et al., 2010) (http://doi.org/10.1073/pnas.1009073107)

Synaptic rearrangment, myelination change cortical thickness

- Cortical thickness changes (Gogtay et al., 2004) (http://doi.org/10.1073/pnas.0402680101)



(Shaw et al., 2008) (https://doi.org/10.1523/JNEUROSCI.5309-07.2008)



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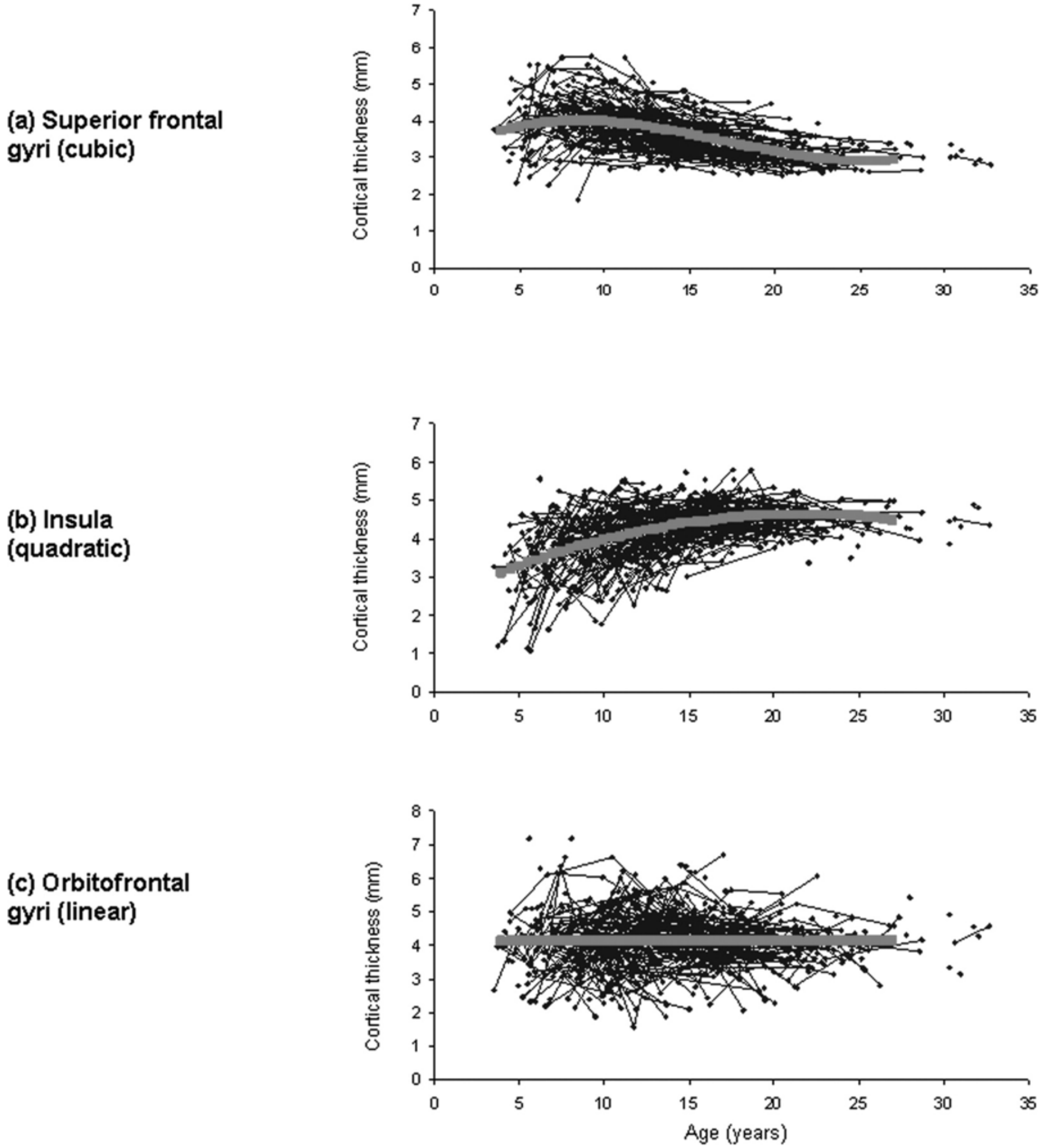
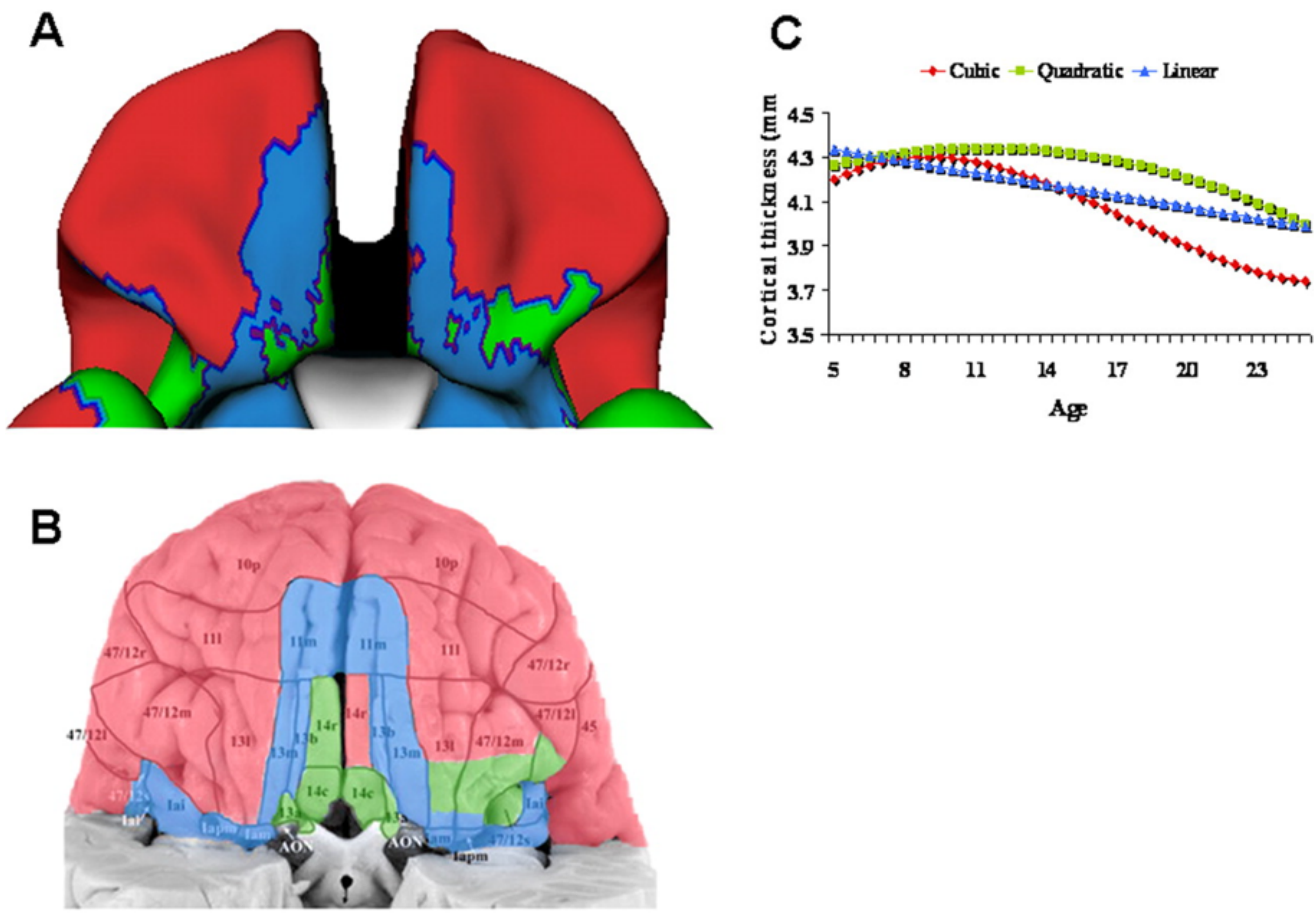


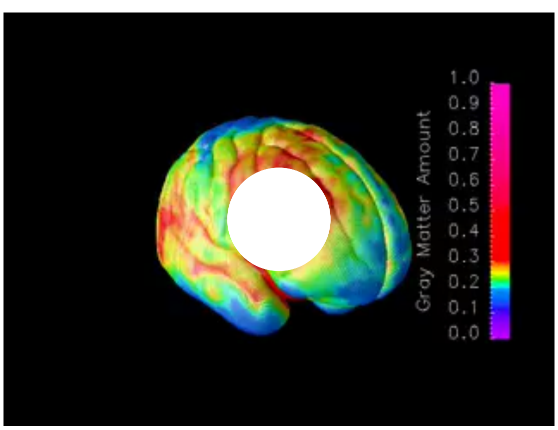
(Shaw et al., 2008) (https://doi.org/10.1523/JNEUROSCI.5309-07.2008)



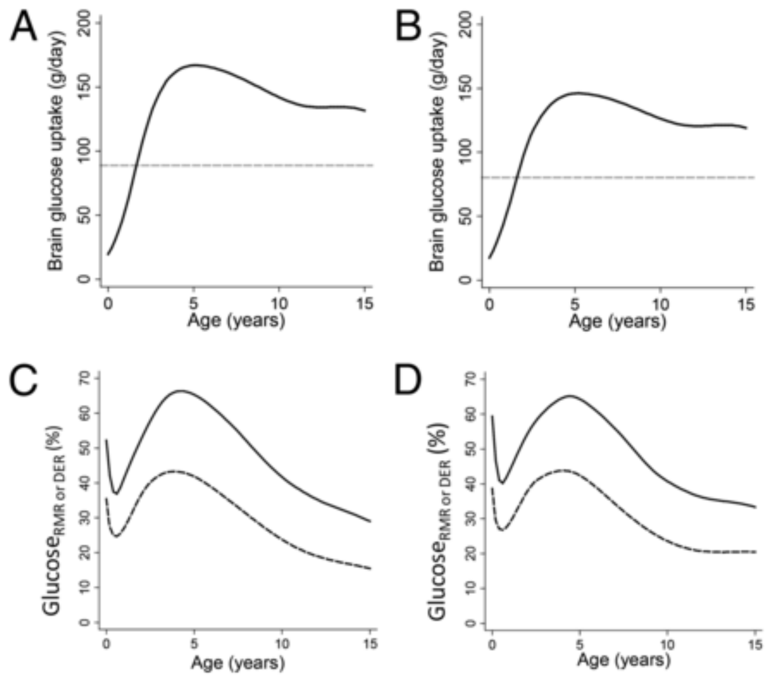
(Shaw et al., 2008) (https://doi.org/10.1523/JNEUROSCI.5309-07.2008)

Video depictions

Right hemisphere | Left hemisphere | Superior | Inferior

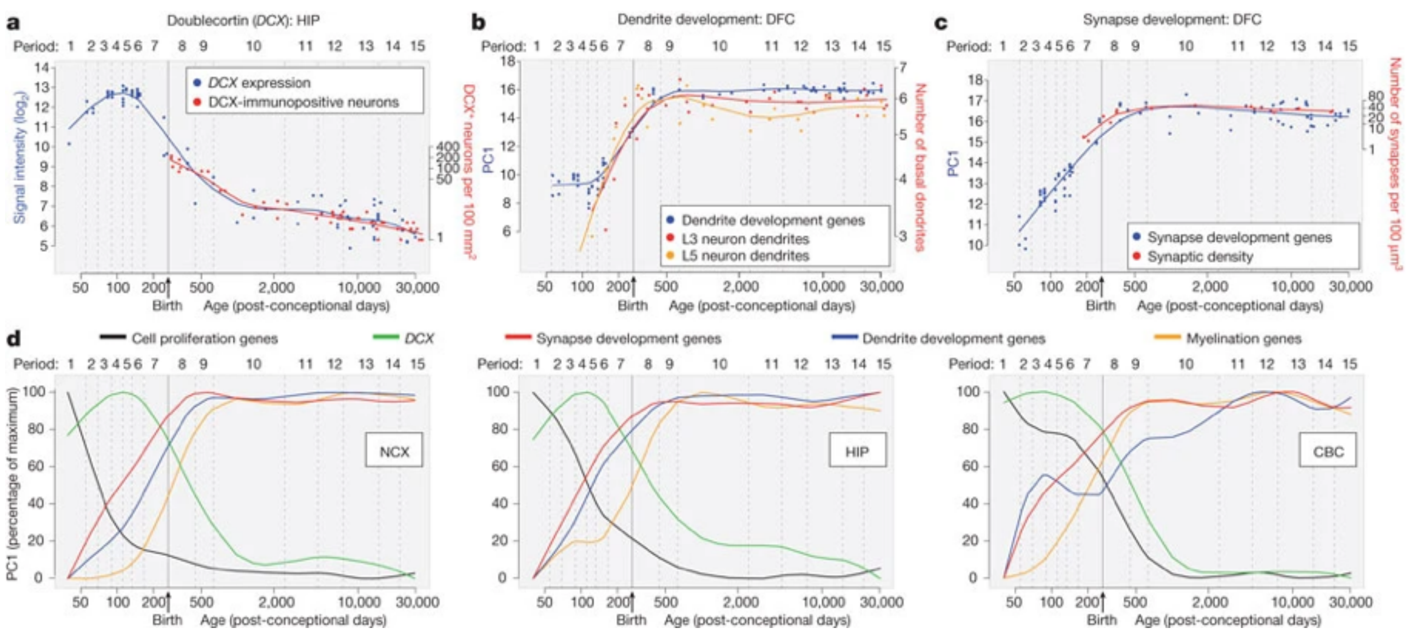


Changes in brain energetics (glucose utilization)



(Kuzawa et al., 2014) (http://doi.org/10.1073/pnas.1323099111)

Gene expression across development



(Kang et al., 2011) (http://doi.org/10.1038/nature10523)

> a, Comparison between DCX expression in HIP and the density of DCX-immunopositive cells in the human dentate gyrus36. b, Comparison between transcriptome-based dendrite development trajectory in DFC and Golgi-method-based growth of basal dendrites of layer 3 (L3) and 5 (L5) pyramidal neurons in the human DFC41. c, Comparison between transcriptome-based synapse development trajectory in DFC and density of DFC synapses calculated using electron microscopy42. For b and c, PC1 for gene expression was plotted against age to represent the developmental trajectory of genes associated with dendrite (b) or synapse (c) development. Independent data sets were centred, scaled and plotted on a logarithmic scale. d, PC1 value for the indicated sets of genes (expressed as percentage of maximum) plotted against age to represent general trends and regional differences in several neurodevelopmental processes in NCX, HIP and CBC.

Summary of developmental milestones

Prenatal

- Neuro- and gliogenesis
- Migration
- Synaptogenesis begins
- Differentiation
- Apoptosis
- Myelination begins
- Infant gene expression ≠ Adult

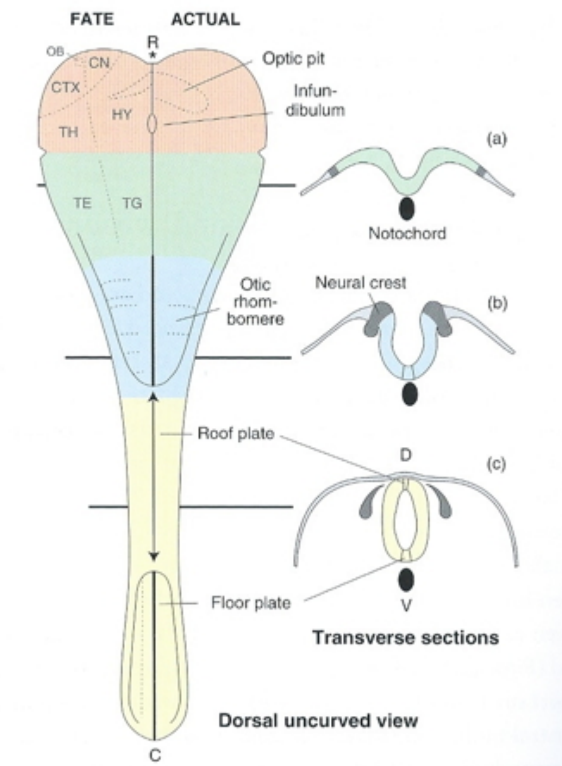
Postnatal

- Synaptogenesis
- Cortical expansion, activity-dependent change
- Then cubic, quadratic, or linear declines in cortical thickness
- Myelination

- Connectivity changes (esp within networks)
- Prolonged period of postnatal/pre-reproductive development (Konner, 2011) (http://www.hup.harvard.edu/catalog.php?isbn=9780674062016)

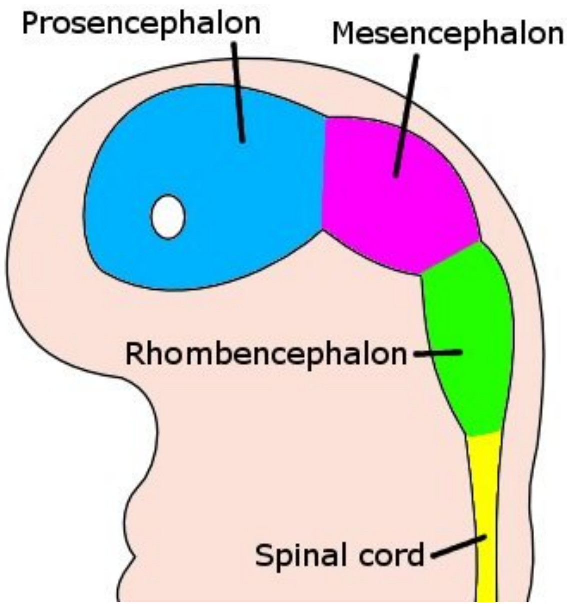
How brain development clarifies anatomical structure

3-4 weeks



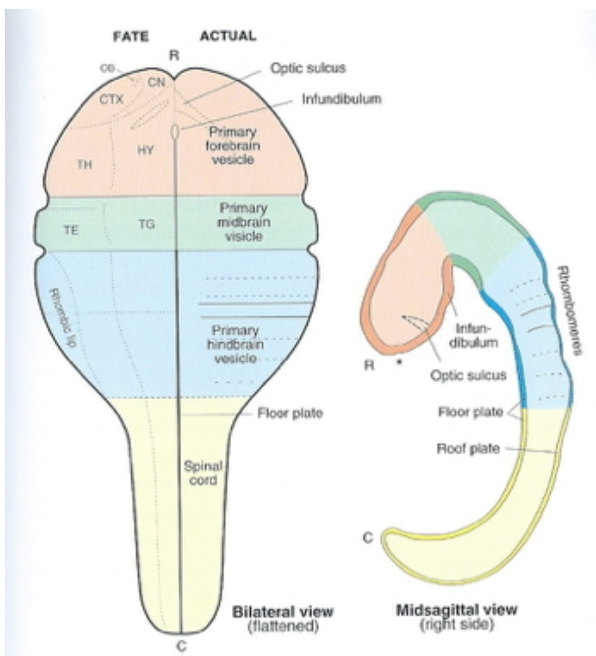
Source: Swanson

4 weeks

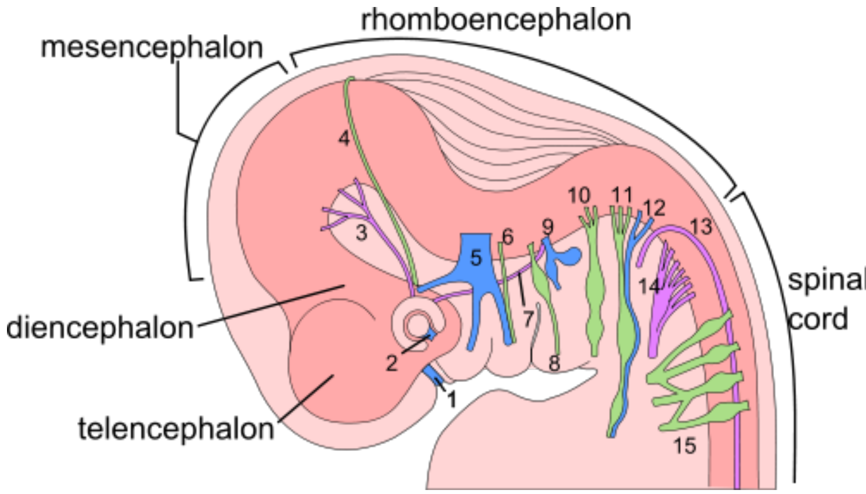


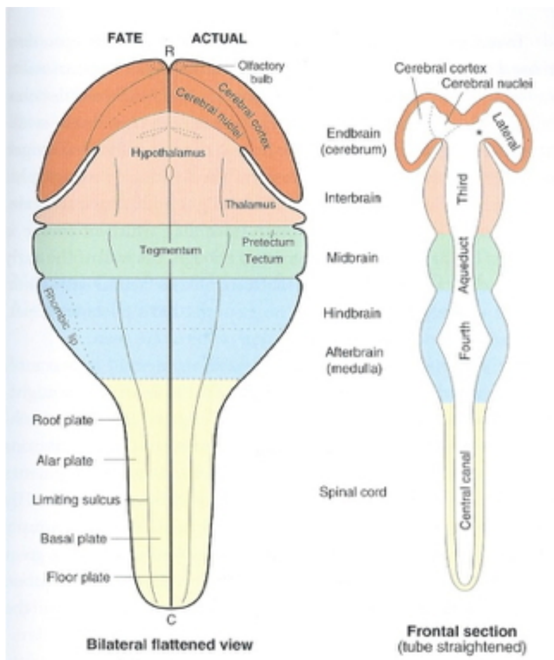
https://upload.wikimedia.org/wikipedia/commons/4/4c/4_week_embryo_brain.jpg (https://upload.wikimedia.org/wikipedia/commons/4/4c/4_week_embryo_brain.jpg)

~4 weeks

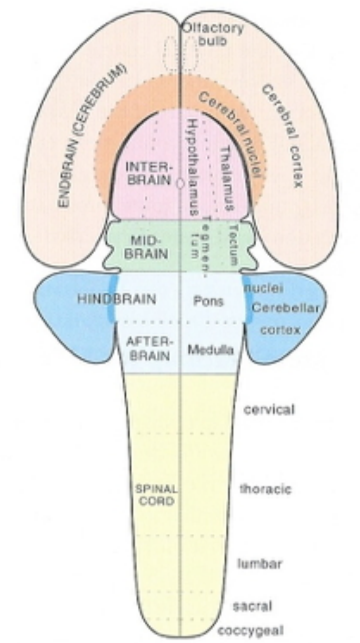


6 weeks





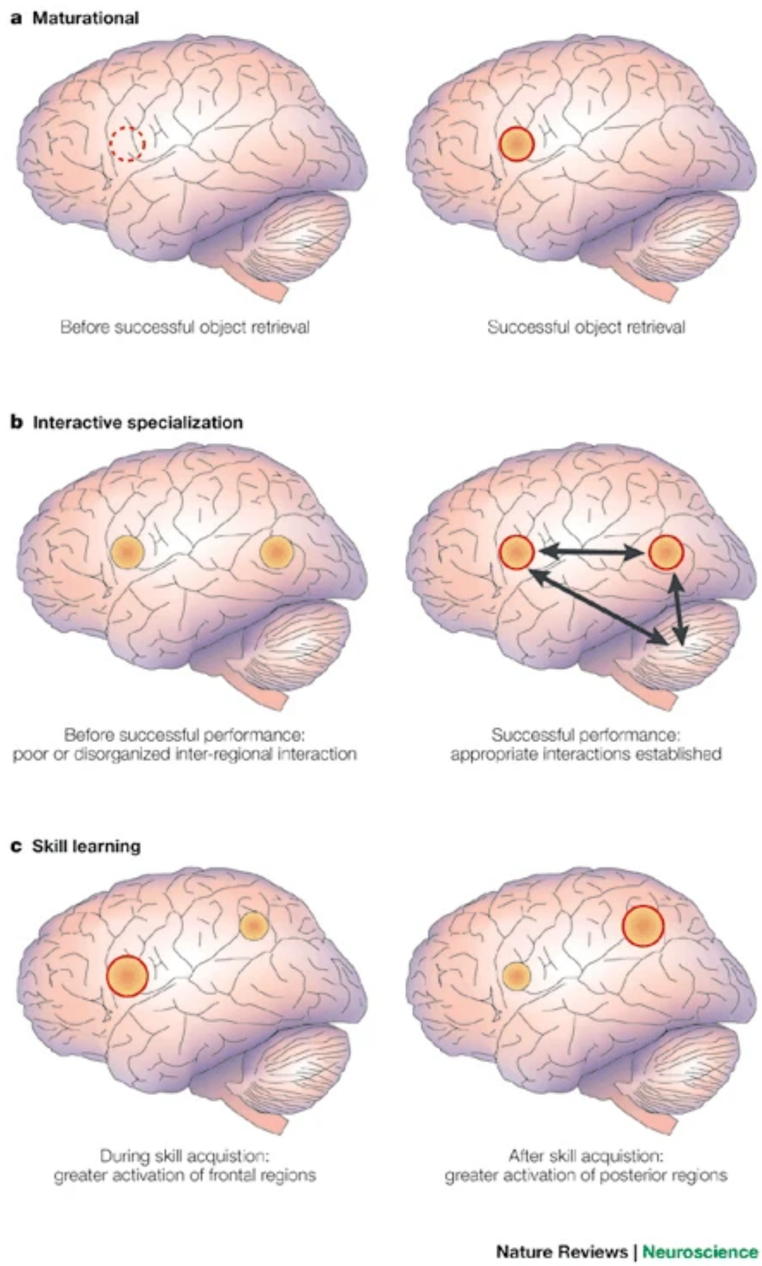
Beyond 6+ weeks



Organization of the brain

Major division	Ventricular Landmark	Embryonic Division	Structure
Forebrain	Lateral	Telencephalon	Cerebral cortex
			Basal ganglia
			Hippocampus, amygdala
	Third	Diencephalon	Thalamus
			Hypothalamus
Midbrain	Cerebral Aqueduct	Mesencephalon	Tectum, tegmentum
Hindbrain	4th	Metencephalon	Cerebellum, pons
	–	Mylencephalon	Medulla oblongata

From structural development to functional development



(Johnson, 2001) (http://doi.org/10.1038/35081509)

Figure 3: Three accounts of the neural basis of an advance in behavioural abilities in infants. a | A maturational view in which the neuroanatomical maturation of one region, in this case the dorsolateral prefrontal cortex (DLPC), allows new behavioural abilities to emerge. Specifically, maturation of DLPC has been associated with successful performance in the object retrieval task (Fig. 1a)50. Note that although the task itself involves activity in several regions, it is thought to be maturation of only one of these, the DLPC, that results in changed behaviour. b | An interactive specialization view in which the onset of a new behavioural ability is due to changes in the interactions between several regions that were already partially active. In this hypothetical illustration, it is suggested that changes in the interactions between DLPC, parietal cortex and cerebellum might give rise to successful performance in the object retrieval paradigm. In contrast to the maturational view, it is refinement of the connectivity between regions, rather than within a single region, that is important. According to this view, regions adjust their functionality together to allow new computations. c | A skill-learning model, in which the pattern of activation of cortical regions changes during the acquisition of new skills throughout the lifespan. In the example illustrated there is decreasing activation of DLPC and medial frontal cortex (pre-supplementary motor area), accompanied by increasing activation of more posterior regions (such as intraparietal sulcus), as human adults perform a visuomotor sequence learning task77. It is suggested that similar changes might occur during the acquisition of new skills by infants. These three accounts are not necessarily mutually exclusive. (Johnson, 2001) (http://doi.org/10.1038/35081509)

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(https://doi.org/10.1523/JNEUROSCI.5309-07.2008)

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