CHAPTER 6: EVOLUTION OF THE VERTEBRATE BRAIN AND BEHAVIOR
Factors related to the evolution of brain size

• Comparative neurology
• Brain size
• Brain-behavior evolution
Factors related to the evolution of brain size

• Comparative neurology

• Brain size

• Brain-behavior evolution
**Process:** adaptive response of the CNS to specific ecological pressures.

- Responsible for novelty and change

**Pattern:** constraints on evolutionary modifiability imposed by inheritance.

- Responsible for stasis and conservatism
Process and pattern in brain structure

Pattern: the same divisions of the CNS are found in all vertebrates.

Process: specializations have led to changes in size and complexity of specific brain structures.

Salmo
(a nonspecialized species)

Gnathonemus
(a mormyrid fish)

Hyperfolded cerebellum of electric fish.
Major concepts in evolutionary theory

- **Homology**: Inherited from a common ancestor (homology).
  - Chimp hand
  - Human hand

- **Homoplasy**: Evolved independently, but have a similar function (homoplasy).
  - Human hand
  - Mantis

- **Divergence**: Modified in one lineage (human) more than in the other (chimp) (divergence).
  - Chimp foot
  - Human foot
Some fundamental concepts

- **Homology**: similarity due to common ancestry.

- **Homoplasy**: similarity due to common ecological pressures.

- **Determining Homology/Homoplasy in the CNS:**
  - Topography
  - Afferent-efferent connections
  - Cytoarchitecture
  - Neurotransmitters
  - Gene expression patterns

- **Polarity**: primitive-derived dimension.

- **Outgroup analysis**: polarity based on character state in closest taxonomic group.
Polarity and outgroup analysis

Outgroup
- Baboon

Ingroup
- Chimp
- Human

- Quadrupedal
- Bipedal

Derived
- Primitive

Quadrupedal
Divisions of the vertebrate CNS

(a) Telencephalon
- Olfactory bulb
- Cerebral hemispheres
- Limbic system
- Striatum

(b) Diencephalon
- Thalamus
- Hypothalamus

Mesencephalon
- Optic tectum

Rhombencephalon
- Cerebellum
- Brain Stem

Anterior (rostral)

Posterior (caudal)
A comparative view of the vertebrate CNS

Key brain innovations in early vertebrates

Gnathostomes (Jawed vertebrates)
- Jaws
- Bone
- 3 semicircular canals
- Loss of prenasal sinus

Osteostracans †
- Paired fins

Galeaspids †

Hetrostracans †
- Paired nasal sacs
- Some fresh water species
- Cerebellum (ocular control)
- Lateral line
- 2 semicircular canals
- Optic tectum (vision)
- Electroreceptors

Lampreys
- Marine habitats
- Lensless eyes
- Nasal openings (olfaction)
- Prenasal sinus

Hagfish

Agnatha (Jawless fish)
Structural and functional properties of the vertebrate CNS

- Telencephalon
  - Pallium and subpallium
  - Eversion and evagination
  - Fish telencephalon and behavior
  - Evolution of the telencephalon
  - Striatum and S-R habits
  - Hippocampus and spatial learning
  - Amygdala and fear learning
  - Evolution of the cortex
  - Cortex in Mesozoic mammals
  - Cortex and learning
Factors related to the evolution of brain size

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Brain evolution: Some basic facts

- Variability in size

- Changes in size across time

- Fossil evidence
Passive growth: allometric increase in brain size relative to body size.

Allometric equation:  \( E = a S^b \)

- \( E \) = brain size
- \( S \) = body size
- \( a \) = constant, point of origin
- \( b \) = constant, slope

Active growth: encephalization.
Passive growth

- Allometric line
- Minimum convex polygon
- Deviation from allometric line

Brain size vs. Body size graph
Minimum convex polygons for various vertebrate classes

Brain Weight (kg) vs. Body Weight (kg)

- Bony fish
- Agnathans
- Amphibians
- Reptiles
- Birds
- Cartilaginous fish
- Mammals
Allometric equations

Allometric growth:

\[ E = a S^b \]

- \( E \) = brain size
- \( S \) = body size
- \( a \) = point of origin
- \( b \) = slope

Log transformation:

\[ \log(E) = \log(a) + b \log(S) \]

Encephalization quotient:

\[ EQ = \frac{E_0}{a S^b} \]
Allometry: log transformation

\[ E = a(S)^b \]

\[ \log(E) = \log(a) + b \log(S) \]
Encephalization: Mammals and reptiles

**Fig. 1**

Mammals and Reptiles: Brain and Body Mass Data

Reptiles: \( \log \text{Brain} = -1.792 + (0.552 \times \log \text{Body}) \) N=62
Mammals: \( \log \text{Brain} = -1.254 + (0.751 \times \log \text{Body}) \) N=301

\( a = \text{point of origin} \)

\( b = \text{slope} \)
Encephalization in various mammalian orders

(A) Marsupials and monotremes

Red kangaroo's brain (5 cm, 56 g)
Encephalization in various mammalian orders

(B) Placental mammals

Brain weight (g)

$10^{-1}$ $10^{-0}$ $10^{0}$ $10^{1}$ $10^{2}$ $10^{3}$ $10^{4}$ $10^{5}$ $10^{6}$ $10^{7}$ $10^{8}$

Body weight (g)

- Primates
- Gliridae
- Artiodactyls
- Toothed whales
- Baleen whales
Evolution of encephalization: birds and mammals

- **Mammals**
  - Large brain

- **Reptiles**
  - Small brain

- **Birds**
  - Large brain

**Derived**

**Primitive**
Factors related to the evolution of brain size

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Principles of brain size

**Functional localization:** allocation of a brain area to a specific function.

**Mass action:** the extent to which brain damage affects a function depends on the size of the damage, rather than its location.

**Proper mass:** the relationship between the size of an area and the functional importance of that area.
Biological intelligence (Jerison, 1973)

**Biological intelligence**: capacity to represent the world

Encephalization in birds

*Archaeopterix*, a fossil bird from the Jurassic (140 Mya).
The forest is a visual nightmare! To discriminate figure from background requires extensive visual processing, which, in turn, may have led to increased brain size in primitive birds.
Biological intelligence (Jerison, 1973)

In Mesozoic mammals, distance perception was probably based on olfaction and audition, both of which place a heavy demand on memory.

Notice the relatively large olfactory bulbs in living nocturnal mammals.

Fossil mammal *Repenomamus robustus* with dinosaur remains in its stomach. Endothermy could allow Mesozoic mammals to hunt at night, when dinosaurs were less active.

Notice the relatively large olfactory bulbs in living nocturnal mammals.
Artificial selection for relative brain size


Method. Since it is impossible to determine brain size in live fish, we sacrificed the parents after offspring production. Brains of those parents were removed and weighed. From the 75 pairs of every population we kept the offspring of the 15 pairs with the relatively largest and smallest brains (controlled for body size) to start (F0) the “up” and “down” selected lines in the three replicates. Within each of these six lines we used two males and females of every family to form 30 breeding pairs for the next generation. We randomly assigned partners, but avoided full-sib pairs. For the F2 generation we followed the same procedure.
Behavioral flexibility: learning sets

(a) +  -  

+  -  +  

-  +  -  

Win-Stay / Lose-Shift

(b) 

(c) 

Percentage Correct on Trial 2

Discrimination Problems

- Rhesus monkeys
- Squirrel monkeys
- Cats
- Rats
- Squirrels

(c) 

Percentage Correct on Trial 2

0 20 40 60 80 100

0 200 400 600 800 1000 1200

Discrimination Problems
Behavioral flexibility: transfer of learning and brain size

<table>
<thead>
<tr>
<th>Trained to Criterion</th>
<th>Overtrained</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original Training</strong></td>
<td></td>
</tr>
<tr>
<td>A+ / B-</td>
<td>C+ / D-</td>
</tr>
<tr>
<td>67% correct</td>
<td>84% correct</td>
</tr>
<tr>
<td><strong>Reversal Training</strong></td>
<td></td>
</tr>
<tr>
<td>A- / B+</td>
<td>C- / D+</td>
</tr>
<tr>
<td>11 trials</td>
<td>11 trials</td>
</tr>
</tbody>
</table>

Transfer Index

\[ TI = (\% \text{ correct } 84\%) - (\% \text{ correct after } 67\%) \]
Positive transfer increases in primates with larger brain size
Spatial memory and hippocampal size in polygynous voles

Polygynous males patrol a large territory and exhibit a larger hippocampus than both female meadow voles and pine voles (males and females).
Genetic variation in vasoppressin receptors and the social behavior of voles

Autoradiograms of vasopressin V1a receptor patterns in the ventral pallidum (VP) of socially monogamous prairie voles and polygamous meadow voles. When V1a receptor levels are artificially increased within the VP of meadow voles using adeno-associated viral vector (AAV) gene transfer (meadow + AAV), they display social behavior that is reminiscent of that of monogamous prairie voles, preferring social contact with their partner over a stranger (20). Error bars indicate SE; asterisks indicate $P < 0.05$. Time in contact is given in minutes.

Spatial memory and hippocampal size in food-storing birds

Hippocampal volume relative to telencephalon volume in 20 different families and subfamilies of food-storing (blue dots) and non-food storing (black dots) bird species (redrawn from Sherry 1989 with additional data presented in Sherry 1996).
In food-storing birds, seasonal change in the hippocampus occurs in fall and winter when the cognitively demanding behavior of caching and retrieving food occurs. A variety of factors, including cognitive performance, exercise, and stress may all influence seasonal change in the avian hippocampus.

Spatial memory and hippocampal size in taxi drivers

Mcguire et al., 2000, PNAS, 97, 4398-403.
Neuroanatomy of language and brain lateralization

**Broca’s area**: control of speech (motor).

**Wernicke’s area**: control of language comprehension (perceptual).

**Arquate fasciculus**: links Wernicke’s area (temporal cortex) with Broca’s area (frontal cortex).
Brain and body size in selected hominids and apes

![Graph showing Brain and Encephalization Quotient (Mya)]

- **Apes**
- **Australopithecus**
- **Homo**
Present

Millions of Years Ago

Early australopithecine burst

Bipedalism?

Relative Brain Size

5 4 3 2 1

Early Homo burst

Stone tools? Omnivorous diet? Cooking?

Social struggle? Language? Culture? Migrations?

Homo sapiens burst

Migrations?