COGNITIVE SCIENCE 107A

Evolutionary Cognitive Neuroscience

Jaime A. Pineda, Ph.D.
UCSD Researcher gets Nobel Prize in Chemistry in 2008

Roger Tsien
Brain Evolution

- **Phylogeny**
  - The study of the evolutionary relationship among species
    - Systematics: science of classification
      - Carl Linnaeus (1707-1778): species, genus, family, order, class, phylum. Based on degrees of similarity and dissimilarity
      - Cladistics: character/feature analysis to reconstruct phylogenetic relationships
        - (Willi Hennig, 1931) - “closely related species are likely to share more biological features or characters” - groups that share a common ancestor -- clades

- **Ontogeny**
  - The study of development, from embryo to adult

*Misconception: ontogeny recapitulates phylogeny*
Specialized Nomenclature

• **Homology**:
  – Similar characteristics in species because they inherited them from a common ancestor. This does not imply identical structure or function.
  • All mammals have an S1 but this can evolve to do functionally different things (e.g., electroreception in monotremes).

• **Analogy**
  – Characteristics that have evolved independently
    • Similarities in function (e.g., ocular dominance columns in primates and some carnivores)
Reasons for Studying Evolution

• Evolutionary changes reflect adaptive responses to an ever changing environment.

• Darwinian evolution has become one of the major organizing principles in science.
  – Provides the basis for organizing the data and making inferences about human behavior
  – Gives context to changes that may not be understood in isolation
  – Helps us understand brain ~ mind relationships

Misconception: Darwinian evolution is highly speculative
Models of Evolution

Ladder: Emphasizes quantitative differences

Tree: Emphasizes qualitative differences

Misconception: Evolution has a single goal or direction.
How Do We Learn About Brain Evolution?

• Fossil record
  – Infer characteristics of brain tissue (e.g., size, shape, and fissures)
  • Pattern of connections determine gyri/sulci (Van Essen, 1997)
    – Dense connections resist separation during growth and form bulges (gyri)
    – Poorly interconnected areas fold more readily forming sulci
    – The folding is reflected in the fissure patterns on the skull
Size of the brain may be related to intelligence but also to other factors!
How… (cont)

Little of the brain’s internal complexity is revealed by studying the fossil record.

• Extant (living) species
  – Comparative neuroanatomy (e.g., 3 main mammalian branches: monotremes, marsupials, placental mammals)
  – Understand the mechanisms and modes of brain evolution
    • Why do all mammals have visual processing in the back?
      – Shared common ancestor (ancestral, homologous, or plesiomorphic features)
      – Independent solution to similar problems (derived, analogous, or apomorphic features)
Assumptions

• Complex life on Earth appears to have evolved only once. It is based on a molecular template that is passed on from generation to generation.

• All multicellular animals are monophyletic (stem from a common ancestor) and thus we share many similarities.

• However, because the molecular template is so highly modifiable, different animals show significant differences.
The Primates
Organizing Principles of Evolution

- What’s the role of a central nervous system?
  - Cnidaria (jellyfish, corals, anemones, hydra)
    - Nerve net (simplest type: 2-layered; distributed)
    - Locomotion, active feeding
    - Sensory (no cross connections)/motor (cross connections) neurons
  - Flatworms (3-layered)
    - Interneurons
    - Bilateral symmetry
    - Clustering of cells (centralization)
    - Rostral specializations (cephalization)
    - Faster and more efficient communication
Functional Significance of Interneurons

- Increase complexity divergence/convergence
- Excitatory/inhibitory switches
- Pattern detectors and generators
- Pacemakers
Next Steps in the Evolution of CNS

- Segmentation and specialization
  - Annelid worms and arthropods: metameres (segments repeated serially along the body’s axis)

- Notochord and dorsal nerve cord
  - Vertebrates
Mammalian CNS

- Subdivided into 3 primary and 5 secondary regions
  - Forebrain
    - Telencephalon (neocortex)
    - Diencephalon (paleo/archicortex)
  - Midbrain
    - Mesencephalon
  - Hindbrain
    - Metencephalon
    - Myelencephalon

Neural plate > neural tube
Some Lessons of Evolution

- Hallmark of the evolution of mammals from reptiles was the emergence of the neocortex
- Current model is the result of millions of years of evolution.
- No master plan
  - not built with specific purpose or design principles
  - responses are to local and immediate needs
- A series of add-on capabilities integrated with what was already there
- Organized and specialized in at least 3 dimensions
  - Anterior-Posterior
  - Dorsal-Ventral
  - Left-Right
Anterior-Posterior Organization
FIGURE 6-2. MacLean's conception of the "triune brain." Three evolutionary stages in the development of the mammalian brain are schematized. The reptilian brain includes the upper brainstem and thalamus. The limbic system developed out of the brainstem in primitive mammals, and the cortex (neocortex) of the forebrain developed out of the limbic system in higher mammals. (From P. D. MacLean, Journal of Nervous and Mental Disease, 1967, 144, pp. 374-382; Reproduced with permission of Williams & Wilkins Co., Baltimore.)
Theory of Brain Organization

NEWEST
Language, thought, VCR instructions

EARLY
Smells, warm emotions, why you'll pay $4 for popcorn

OLDEST
Explains urge to run and hide from Pee-Wee Herman
Figure 2-11. Projection of visual field to the cortex in relation to certain motor mechanisms in the commissurotomized patient. (Reprinted from "Hemisphere disconnection and unity in conscious awareness" by R. W. Sperry, American Psychologist, 1968, 23, 728. Copyright 1968 by American Psychological Association, Washington, D.C. Reprinted by permission.)
Features of Mammalian Evolution

• The size of brain parts is highly predictable from absolute brain size by a linear/non-linear function.
• The order of neurogenesis correlates with later generating structures.
  – Telencephalon shows greater development than other regions
  – Increased size of associational areas
• There is increased laminar differentiation
• There is increased circuitry for biophysical senses
  – Vision, audition, sensation compared to chemical senses such as olfaction and taste
• There is increased density and diversity of cell types.
• There is an increased number of specialized areas.
• There is increased myelination (preservation of conduction times).
Relationship of Brain Parts

Spearman's $r=0.95$, $P<0.0003$)
“Associational” areas increase as a percentage of total brain

16%  80%
Brain Complexity Produces Increased Lamination Which Produces More Complex Behavior
Origin of the Neocortex

• Divided into three parts
  – Lateral paleocortex $\rightarrow$ olfactory piriform cortex
  – Medial archicortex $\rightarrow$ hippocampus and subiculum
  – Neocortex or isocortex $\rightarrow$ overlying cortex

• Divided into six layers

• Diverse neuron types
A Common Ancestor

- Six layers of cortex
  - 1 cell free zone
  - 2-3 cortico-cortical connections
  - 4 receives thalamic input
  - 5 output to subcortical areas
  - 6 output to thalamus
- Columnar organization (30-50 um; ~110 cells/column)
- Mammalian cortex subdivided into 10-30 different specialized areas
- Primary areas surrounded by secondary and tertiary areas
- Visual area in back
- Somatosensory in front
- Auditory in between
A Common Ancestor
Non-Human Primate
Further Evidence for a Common Ancestor

Fig. 5. Phylogeny of the middle temporal visual area. All primates possess a visual area, located in the temporal cortex, termed the middle temporal visual area (MT). This visual area receives direct projections from the primary (V1) and secondary (V2) visual cortices, and its cells are highly sensitive to the direction of moving stimuli. Given the presence of a similar temporal visual field (dark red) in all prosimians, New World (ceboid) monkeys and Old World (cercopithecoid) monkeys, this visual field is presumed to be homologous among primates, and therefore present in the earliest primate. Although other members of the archontan radiation (tree shrews, flying lemurs and bats) do not possess a comparable temporal visual area, megachiropterans and tree shrews (tupaiids) do possess a visual area (light red) adjacent to the secondary visual cortex (yellow) that possesses some of the characteristics of the middle temporal visual area of primates. Thus, it is possible that this visual area in tree shrews and other nonprimate archontans is homologous to the MT of primates and represents the primitive condition for archontans. If so, primates exhibit a derived condition, in which this visual area is displaced from the rostral border of V2. A similar displaced visual field, the Bishop–Claire region, occurs in cats. If displaced temporal visual areas in carnivores and primates have both evolved from a tupaiid-like pattern, they must be interpreted as a case of parallel homoplasy.
Support for Quantitative Changes

Fig. 1. Sizes of 10 measured brain subdivisions from 131 species plotted as a function of total brain size (orange squares, simians; green circles, prosimians; red circles, insectivores; and blue squares, bats). This method of representation emphasizes the linearity of the relation between brain sizes and structure sizes across mammalian groups on logarithmic scales. Each scatterplot of data points corresponds to a brain subdivision. Arbitrary constants (in parentheses after each subdivision name) were added to separate the plots visually; their normal overlap can be seen in Fig. 2A. Table 1 lists the slopes and intercepts of each regression equation for each structure.

Finlay and Darlington (1995)
Support for Qualitative Changes

Echolocation  Electroreceptive  Olfaction

Fig. 2. The organization of neocortex in highly derived species. Subdivisions of cortex in animals with sensory specializations such as the echolocating ghost bat, the electroreceptive platypus, and the star-nosed mole. More than half of the cortex of the ghost bat is involved in processing auditory information (black + Aud), while approximately two-thirds (including SI, PV, R and M) of cortex in the platypus is involved in processing inputs from the bill (either electrosensory or mechanosensory, or both, red). In the star-nosed mole, visual cortex (V, yellow) is very small, and a large area of cortex is devoted to processing inputs from the nose. Despite the dramatic modifications in terms of size, internal organization, and the addition of modules in these species, components of a common plan of organization can still be identified (depicted in the same colours). Subdivisions of the ghost bat cortex are redrawn from Ref. 29 (somatosensory) and L. Krubitzer (unpublished observations) (visual and auditory). Subdivisions of the platypus cortex are redrawn from Ref. 1, and those of the star-nosed mole cortex are redrawn from Ref. 30. Medial is at the top and rostral is to the right. Scale bars, 1 mm.
Qualitative Differences (laminar specializations)

Squirrel monkey  Cynomolgus

5-HT
serotonin

NA
norepinephrine
Evolution of Primates

- Evolved 60-70 million years ago (following extinction of dinosaurs)
  - Prosimians
    - Lorises, lemurs, bushbabies
    - Small-bodied, nocturnal, ate insects and fruits
    - Forward facing eyes, moist noses, large olfactory system, opposable thumbs
  - Tarsiers?
    - Prosimian-like animals
  - Anthropoids (evolved from prosimians ~ 35 M yrs ago)
    - Diurnal; Dry noses; reduced olfaction, enhanced vision, larger bodies, larger social groups.
Evolution of Primates (cont.)

• Monkeys-apes split from arthropoids about 15-25 million years ago
• 9 M years ago apes separated from human/chimps
• A line of apes diverged about 5-6 million years ago into two branches
  – Chimps and bonobos
  – hominids
The First Humans

- Australopithecus; “Lucy” (4.0 mya)
- Homo habilis; “Handy Man” (2-2.5 mya)
- Homo erectus; first to migrate (1.8 mya)
- Neanderthals (130-200K ya)
- Homo sapiens (1 M ya) and Cro-Magnon (modern Homo sapiens -35,000 ya)
- Multiregional model (parallel evolution)
- “Out of Africa” (replacement evolution)
Encephalization

• The fraction of gross brain size that represents neuronal processing capacity that is not related to body size
  – Nocturnal → diurnal vision in early mammals
  – Frontally placed eyes (and stereoscopic vision)
  – Higher precision and control of musculature
  – Complex social environment
  – Changes in diet
Encephalization Quotient (EQ) - rough estimate of intelligence

(ratio of the actual brain mass to the expected brain mass of a typical animal that size)
The Evolution of Cognition: Why are We Smart?

• Complex social relations among higher primates
  – Monkeys as opposed to apes have similar complex social
environments – so why are their cognitive capabilities so different?

• Complexities involved in obtaining a varied diet
  – Chimps hunt and gather a wide variety of foods, however, gorillas
    feed on a very simple diet and don’t wander as far.

• Complexity is not in finding food but in extracting it
  – Chemicals that taste bad or are lethal
  – Encased food (e.g., coconuts)
  – High nutrient foods
The Evolution of Cognition: Why are We Smart? (cont.)

• Strategies developed
  – Change in digestive system to handle lots of low nutrient foods
  – Behavioral strategies to search for high quality, easy to digest foods
    • Use of tools
    • Increased memory
    • Better recognition
    • Verbal signals
Different Strategies Led to Differences in Digestive Systems

Colobine

Colobus guereza

ALKALINE FORESTOMACH CONTAINING CELLULOLOYTIC BACTERIA

ACID STOMACH

CECUM

COLON

SMALL INTESTINE

Vervet

Cercopithecus pygerythrus

ACID STOMACH
Different Strategies Led to Differences in Brain Size

SPIDER MONKEY
(Ateles geoffroyi)

TYPICAL DIET
Fruits: 72 percent
Leaves: 22 percent
Flowers: 6 percent

WEIGHT
Six to eight kilograms

BRAIN SIZE
107 grams

DAY RANGE
915 meters

DIGESTIVE FEATURES
Small colon
Fast passage of food through colon

HOWLER MONKEY
(Alorcatta palliata)

TYPICAL DIET
Fruits: 42 percent
Leaves: 48 percent
Flowers: 10 percent

WEIGHT
Six to eight kilograms

BRAIN SIZE
50.3 grams

DAY RANGE
443 meters

DIGESTIVE FEATURES
Large colon
Slow passage of food through colon

SPIDER MONKEY (left) is a fruit specialist, whereas the howler monkey (right) eats large quantities of leaves. The author proposes that diet played a major role in shaping the different traits of the two like-sized species, which shared a common ancestor. Natural selection favored a larger brain in spider monkeys, in part because enhanced mental capacity helped them remember where ripe fruits could be found. And spider monkeys range farther each day because in any patch of forest, ripe fruits are less abundant than leaves. The digestive traits of spider and howler monkeys promote efficient extraction of nutrition from fruits and leaves, respectively.
The Hunting Apes : Meat Eating and the Origins of Human Behavior
by Craig B. Stanford

Editorial Reviews
Most evolutionary biologists agree that what makes humans unique among animals is our brainpower. But why--and how--did we evolve our oversized brains? Craig Stanford dusts off the old "Man the Hunter" theory, roundly criticized as replete with bad (and sexist) assumptions, and finds a thick, juicy, postmodern steak at the heart of it. He argues, "The origins of human intelligence are linked to the acquisition of meat, especially through the cognitive capacities necessary for the strategic sharing of meat with fellow group members."

Stanford studied the great apes, especially chimpanzees, and came to the conclusion that among primates, meat is a valuable commodity both nutritionally and socially. Although many other foods are nutritionally desirable, meat is unique in its social desirability, and for males, it represents power:
Underlying the nutritional aspect of getting meat, part of the social fabric of the community is revealed in the dominance displays, the tolerated theft, and the bartered meat for sexual access. The end of the hunt is often only the beginning of a whole other arena of social interaction. In Stanford's view, females play a crucial role in keeping groups together and cementing individual relationships. Meat plays an important role in the way males fit in to a society, and the ability of males to get meat readily may very well explain their societal dominance. These conclusions are not liable to be nearly so controversial as the way Stanford gathered his data--he drew broad parallels between chimps and modern hunter-gatherer societies. Stanford also admits that a lack of fossil evidence supporting his meat/brain link is problematic. The Hunting Apes is an interesting look at what is likely the worthwhile center of a discredited evolutionary theory. -- Therese Littleton
What Makes Humans Different?

- Language
- Self-consciousness
- Pedagogy
- Theory of Mind (attributing beliefs to others)