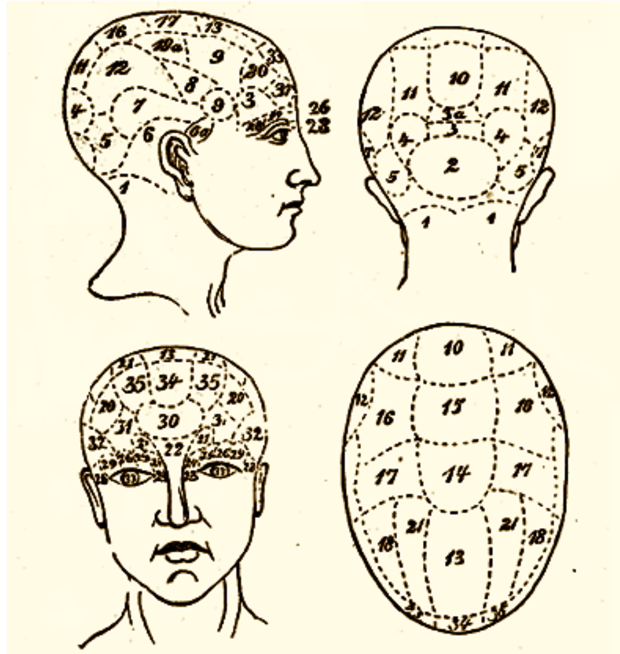
MODELING: WHAT IS THE HUMAN BRAIN FOR?

What model can we construct to explain what it is that the human brain is doing in general? Indeed, what is a human brain for?

- *Faculty Psychology* (Describing the mind as a collection of separate powers or functions)
    - Jerry Fodor's (1983) *Modularity of Mind*
- *Localizing Models* (Discovering individual regions and their associated functions: Broca, Wernicke, Penfield, etc.)
- *Hierarchical & Connection Models* (Establishing order and patterns of functional activity)
    - Geschwind's Disconnection Syndrome Model (1965)
    - Aleksandr Luria's 3-Unit Sequential Model of Functional Networks (Luria, 1966)
    - Distributed Hierarchical Processing Model (Fellerman & VanEssen, 1991)
- *Models from Darwinian Theory & Evolutionary Psychology*
    - Neural Darwinism (Gerald Edelman)
    - Massive Modularity Hypothesis (Modularity of Mind)
- *Predictive Coding (Bayesian) Model* (Karl Friston, Andy Clark, Lisa Feldman Barrett, et al.)

1. Faculty Psychology: The mind as a collection of separate powers or functions

Before and even up to the end of the 19th century, the mind was conceived as functioning as a collection of separate powers. Medieval philosophers and theologians like Thomas Aquinas taught this theory. Even after the Enlightenment, various forms of faculty psychology continued to be important, for example, the Scottish philosopher Thomas Reid and, most importantly, the phrenology of Franz Joseph Gall (1758-1828) and his early collaborator, Johann Spurzheim (1776-1832).



A Chart of Phrenology.
1 Amativeness : 2 Philoprogenitiveness ; 3 Concentrativeness ; 3 a Inhabitiveness ; 4 Adhesiveness ; 5 Combativeness ; 6 Destructiveness ; 6 a Alimentiveness ; 7 Secretiveness ; 8 Acquisitiveness ; 9 Constructiveness ; 10 Self-esteem ; 11 Love of Approbation ; 12 Cautiousness ; 13 Benevolence ; 14 Veneration ; 15 Firmness ; 16 Conscientiousness ; 17 Hope ; 18 Wonder ; 19 Ideality ; 19 a (Not determined) ; 20 Wit : 21 Imitation ; 22 Individuality ; 23 Form ; 24 Size ; 25 Weight ; 26 Coloring ; 27 Locality ; 28 Number ; 29 Order ; 30 Eventuality ; 31 Time ; 32 Tune ; 33 Language ; 34 Comparison ; 35 Causality. [Some raise the number of organs to forty-three.]

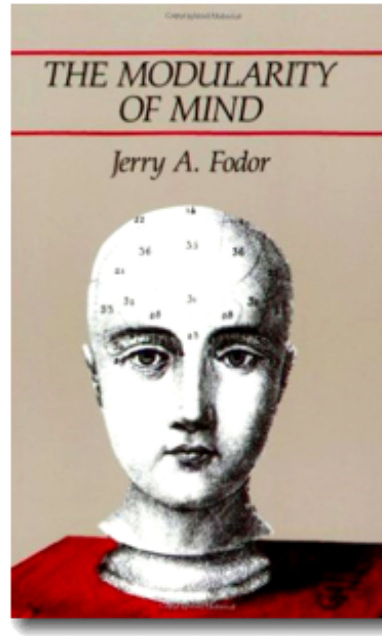
In their theories, these various powers of the mind were considered to be inborn, distinct, and actively influencing behaviors and habits. Examples of such faculties include *attention*, *language*, *memory*, *reasoning*, and *volition* (*will*).

The phrenologists of the 19th century multiplied the number of supposed faculties until they reached several dozen. These included abilities such as *amativeness* (the capacity to love), *benevolence*, *self-esteem*, *firmness*, *conscientiousness*, *hope*, *wonder*, *language*, *acquisitiveness*, etc.

While we know that the phrenologists were wrong in the way they imagined these "faculties of the mind", their efforts to associate each faculty with a specific region of the head represent the first efforts at localizing brain functions.

JERRY FODOR'S (1983) *MODULARITY OF MIND*

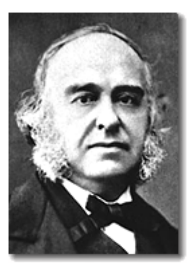
- Influenced by Noam Chomsky's notion of an innate (in-born) "language acquisition device" (LAD), cognitive research on the ways that optical illusions are perceived, AND Gall's original thesis about faculty psychology (!). Hence, while Fodor rejects Gall's location theories about where each faculty was located on the surface of the brain, he argues that Gall was essentially right that the mind does have relatively discrete faculties.
- The mind is principally composed of multiple "autonomous cognitive *[input & output]* sub-systems" (Bermudez, 2014, p. 285) that operate as domain-specific information processing modules.

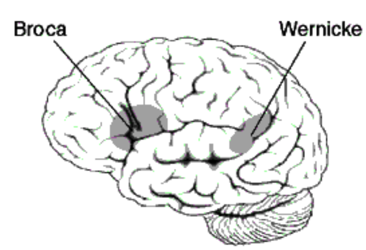


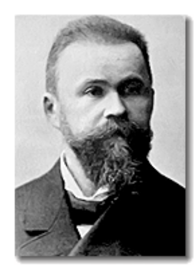
- Information in each module is *encapsulated*, that is, it is processed without being affected by the rest of what is happening in the mind.
- Each module responds *automatically or in mandatory fashion* to the stimuli it receives according to its dedicated concerns. There is no need for a central executive to direct a module to function [if visual data is presented to the visual module, it will process it automatically.]
- Modules process information at a *fast speed*
- The output of modular processes are simple (or "shallow')
- The *architecture* of the nervous system is *more or less fixed*.
- Possible cognitive modules include *color perception, shape analysis, face recognition, analysis of three-dimensional spatial relations, visual guidance of body movements, recognizing the voices of other humans, grammatical analysis of spoken sounds* et al. (Bermudez, 2014, p. 289).
- HOWEVER, Fodor also argues that the mind <u>does</u> employ non-modular central processing in order to correct errors and regularize the output across the various cognitive modules. Included in this form of central processing is an organism's belief system that, as a whole, functions as an integrated "theory of the world." As an organism experiences errors and challenges to its belief system, the beliefs (and thus, an individual's theory of the world) will change. However, the functioning of the cognitive modules *per se* (which are almost always on the interface between the organism and its environment) tends to operate outside of the control of this central processing system. So, for example, even though we may know and appreciate how a visual illusion works, we still see the illusion since the perception is not affected by our knowledge (belief).

2. LOCALIZING MODELS: DISCOVERING INDIVIDUAL REGIONS AND THEIR FUNCTIONS

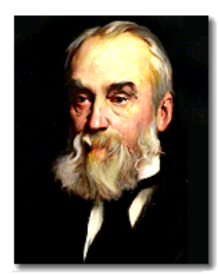
- In 1861 the French neurologist, **Paul Broca** (1824-1880), identified damage to the left frontal lobe as causing impairment in spoken language, more specifically, an inability to speak fluently or even complete absence of any speech. This difficulty is known as expressive or Broca's aphasia.







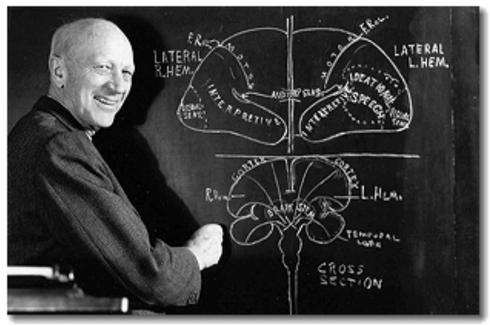
- In 1874 the German neurologist, **Carl Wernicke** (1848-1905), described a form of language impairment associated with damage to the dorsal superior region of the left temporal cortex. Patients with this type of lesion appeared to be able to speak with some fluency, but they did not comprehend what they heard and the speech they produced was often nonsensical or meaningless. This "fluent" aphasia is often called receptive or Wernicke's aphasia.
- In 1870, the British neurologist, **John Huglings Jackson** (1835-1911), proposed that different areas of the cortex were responsible for the movement of different parts of the body. His proposal was based on observations of patients with partial/unilateral/"motor" epileptic seizures in which the seizure appeared to travel or march ("Jacksonian March") in a specific direction from one area of the body to another (e.g., from the hand to the shoulder or from the head to the

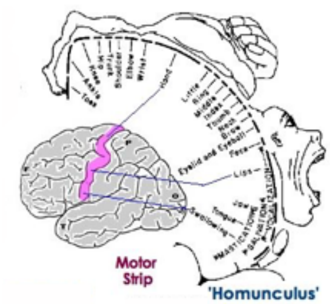


J. Hughlings Jackson, MD

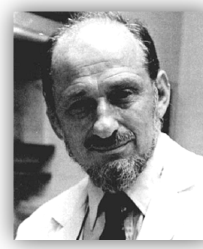
fingers). He argued that there was a correspondence between specific areas of the cortex and specific muscle groups of the body. He didn't understand specifically was happening, but defined epilepsy as "the name for occasional, sudden, excessive, rapid, and local discharge of grey matter" (Hughlings Jackson, 1873 quoted in York & Steinberg, 2011, p. 3109).

- In 1870, the German physiologists, **Gustav Fritsch** (1838-1927) and **Edvard Hitzig** (1839-1907) demonstrated that electrical stimulation of the cortex would induce movement in the limbs of a dog. This finding confirmed Hughlings Jackson's supposition and was further extended by David Ferrier (1843-1928) in 1873 in studies of the motor cortex of primates.
- The great US/Canadian neurosurgeon, **Wilder Penfield** (1891-1976), and his collaborators at the Montreal Neurological Institute charted the regions of the sensory and motor cortices by probing the surface of the brains of patients on the operating table. He produced the famous "homunculus" maps that were initially published in 1951. He further probed the temporal and parietal lobes and argued that the temporal lobe was particularly the location for the recall of various sensory experiences as well as provoking various emotional states (e.g., fear, spiritual or religious feelings, et al.)



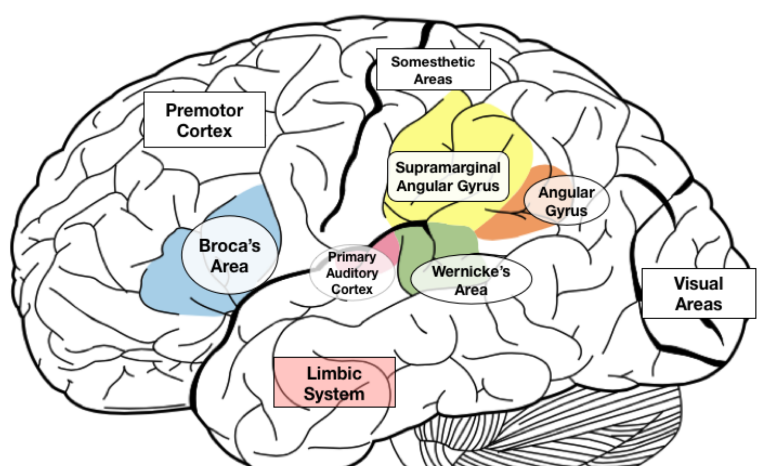


3. Hierarchical and Connection Models

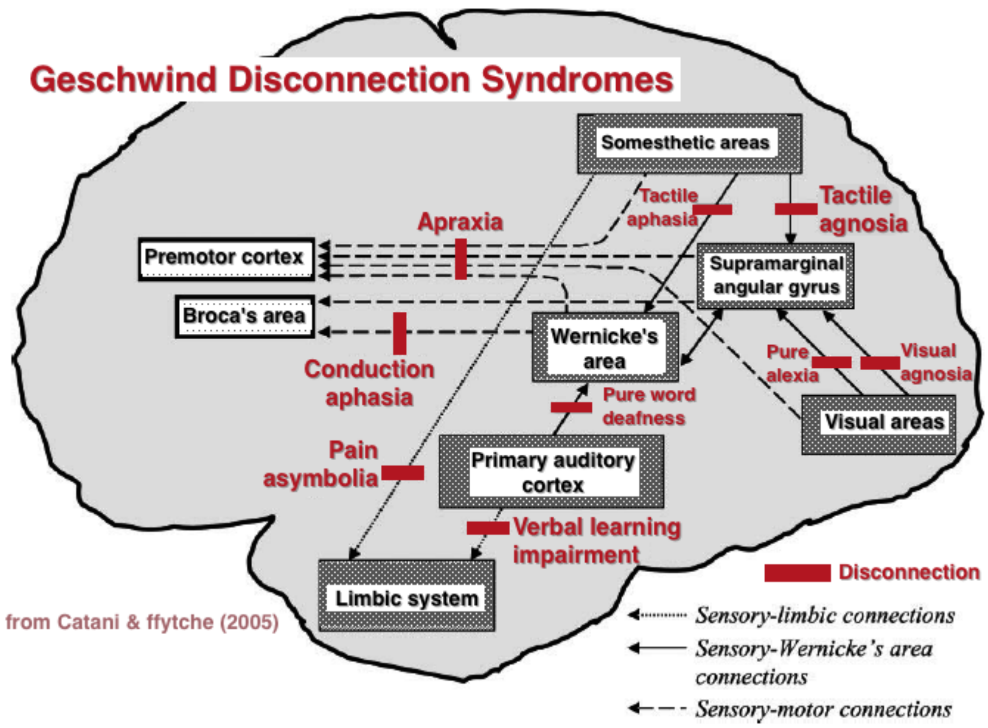


A. *GESCHWIND DISCONNECTION SYNDROME MODEL* (Catani & ffytch, 2005; Mesulam, 2015)

- In 1965, Norman Geschwind (1928-84), the premier neurologist in Boston in the 1960s and 1970s, published the foundational two-part text in behavioral neurology, *Disconnexion Syndromes in Animal and Man* (1965 a, b).
- Geschwind argued that, if neurology wants to understand what goes wrong in brain injuries & diseases, it should (1) **look closely at individual case studies**; (2) **pay closer attention to functional rather than topographical features of the cerebral cortex**; (3) **understand that brain connections follow hierarchical patterns**, and (4) **look toward animal models** (e.g., with monkeys) to better understand how human brains function (Mesulam, 2015).
- Geschwind demonstrated that multiple neurological symptoms such as aphasia and agnosia can be understood as deficits arising from the broken connections from one area of the cortex to another. As Marcel Mesulam (2015) explains, " the one common denominator for

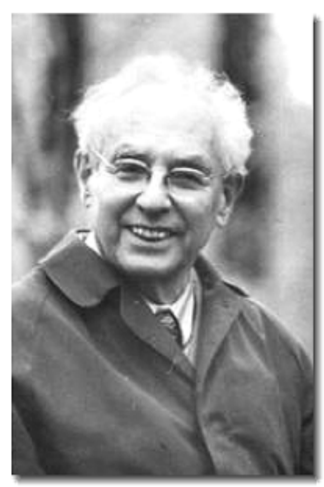


"Brain Surface Gyri" by James.mcd.nz - self-made - reproduction of combined images Surfacegyri.JPG by Reid Offringa and Ventral-dorsal streams.svg by Selket. Licensed under GFDL via Wikimedia Commons - https://commons.wikimedia.org/wiki/File:Brain_Surface_Gyri.SVG#/media/File:Brain_Surface_Gyri.SVG all the phenomena he covers is the selective interruption of information flow along a mono- or multisynaptic route (callosal, motor, visual, auditory, tactile, limbic) in a setting where the points of origin and termination display a relative preservation of other connections and functions. Using this phenomenon of selective dissociation as its core construct, *Disconnexion Syndromes* offered an anatomically-anchored and unified explanation of phenomena that until then appeared to have little in common and outlined principles of connectivity that guided an entire generation of experimental neuroanatomy" (p. 2795).



B. LURIA'S 3-UNIT SEQUENTIAL MODEL OF FUNCTIONAL NETWORKS

Aleksandr Romanovich Luria (1902-1977)



- Soviet neuropsychologist and developmental psychologist
- Worked with Lev Vygotsky in the 1920s & 1930s on “Cultural-Historical Psychology” (the role of culture and language in the development of higher mental functions).
- From his early experiences he came to understand that the mind is always mediated through culture: "the analysis of complex cultural mechanisms is the key to the understanding of the simple neurodynamical processes" (Luria, 1932, p. 428 quoted in Cole, 2002)
- He went to medical school in the late 1930s and worked at the Moscow Institute of Psychology
- The rest of his life was devoted to the advance of clinical neuropsychology. In the Soviet Union & Russia, the study of individual with brain damage is known as *defectology*.

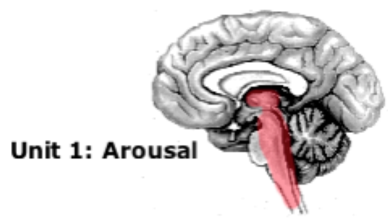
- Very well known for the popular case studies of S. V. Shereshevskii who seemed to have an unlimited memory (*The Mind of a Mnemonist*, 1968) and Zasetsky, a soldier who recovered from a severe head wound (*The Man with a Shattered World*, 1972).
- His most important professional books included the crucial volume, *Higher Cortical Functions in Man* (1966) and the briefer summary, *The Working Brain* (1973). His autobiography (1979) was published shortly after his death.

"Luria defined brain function as the common task executed by a distributed brain network of complex dynamic structures united by the demands of cognition" (Bressler, 2014, p. 438).

"a function is, in fact, a ***functional system***...directed toward the performance of a particular biological task and consisting of a group of interconnected acts that produce the corresponding biological effect. The most significant feature of a functional system is that, as a rule, it is based on a complex dynamic 'constellation' of connections, situated at different levels of the nervous system, that, in the performance of the adaptive task, may be changed with the task itself remaining unchanged" (Luria, 1966, p. 24, emphasis added).

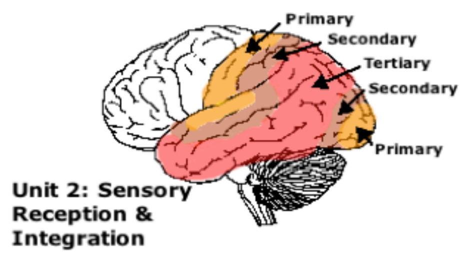
Unit 1 Arousal

- Filtering of sensory input
- Controlling the overall level of arousal or the "tone" of the cortex



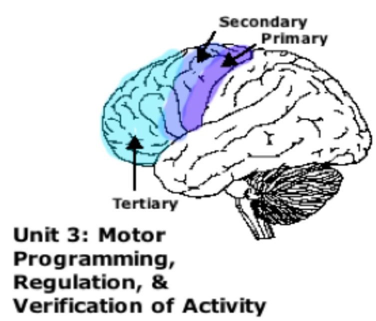
Unit 2 Sensory Reception and Interpretation

- Primary Zone = Reception of Sensory Input
- Secondary Zone = Analysis, coding, and storing information
- Tertiary Zone ("Association Cortex") = Information integration across sensory modalities



Unit 3 Programming, Regulation, & Verification of Activity

- Motor Cortex = Initiation of activity
- Premotor Cortex (Secondary) = Analysis, organization, and sequencing of activity
- Tertiary Areas = Intentions, planning, mental flexibility, oversight (executive control & review)



Note that the sequence across Units 2 and 3 follows a reversed pattern

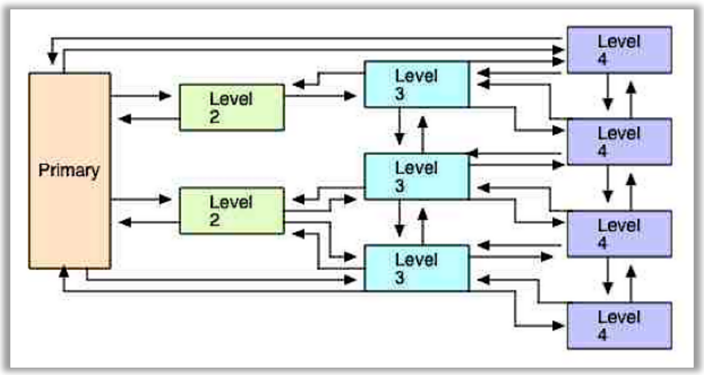
Primary → Secondary → Tertiary → Tertiary → Secondary → Primary
(Unit 2) (Unit 3)

C. *DISTRIBUTED HIERARCHICAL MODEL* (Felleman & Van Essen, 1991)

Theoretical Model (below left)

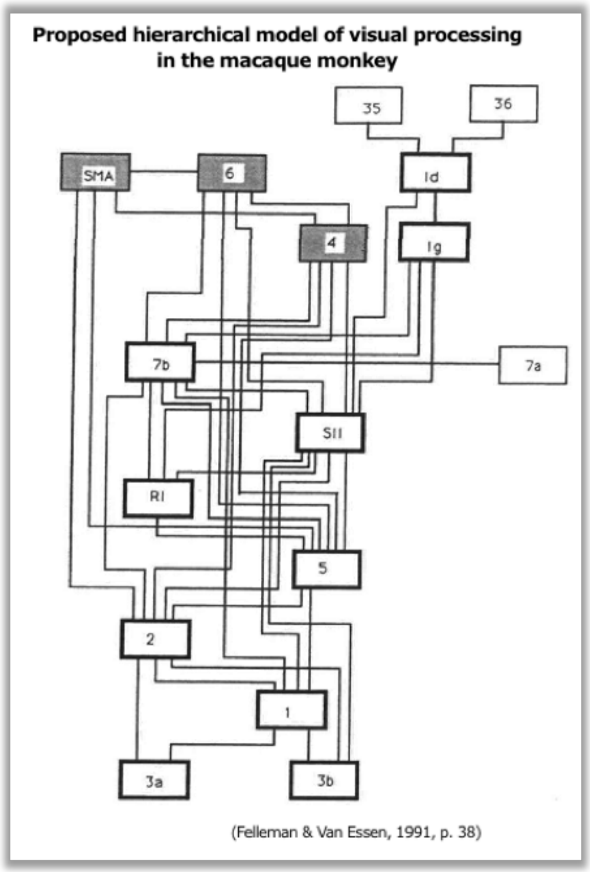
- Hierarchically organized
- More than one area occupies a particular hierarchy = ***parallel processing**** (see below)
- **Forward and backward connections!***
- Based on research with macaque monkeys
- The actual model (below right) contains 10 cortical levels of processing for visual data plus 4 other levels (retina, lateral geniculate nucleus at bottom & entorhinal cortex & hippocampus at top).

* this features is missing in Luria's model



Daniel Felleman

David Van Essen



Proposed hierarchical model of visual processing in the macaque monkey

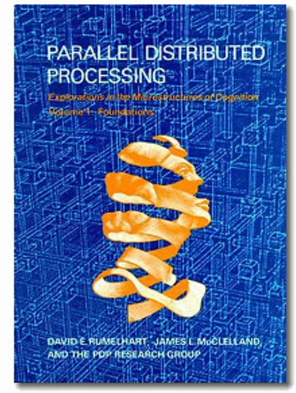
(Felleman & Van Essen, 1991, p. 38)

Parallel Distributed Processing (PDP)

- In the 1970s computer designers began to implement strategies in which computing individual problems would be broken up into different components and each of these would be computed by a separate processing unit at the same time, that is, *in parallel*. When the processing units completed their work, the results would be combined provide an answer or outcome to the problem. Prior to this, problems were computed *serially*, that is, each phases of the analysis was processed step-by-step by a single central processing unit. The advantage of PDP computing was to speed up how much data and how quickly the data could be processed.

- In the 1980s, the psychologists, David E. Rumelhart (UC San Diego & Stanford) and James L. McClelland (Stanford), and the PDP Research Group applied this new model of computing to the human brain in two seminal books: *Parallel Distributed Processing: Explorations in the Microstructure of Cognitio*n, Vol. 1 (Foundations, 1986) and Vol. 2 (Psychological and Biological Models, 1986). At the heart of their analysis was the notion of the nervous system as a "neural net" in which multiple incoming stimuli were acted upon simultaneously (in parallel) across the network (distributed) following a set of fundamental rules.

- While further analysis of the PDP lies beyond the needs of this class, you should note that the model of Felleman and Van Essen as well as later "connectionist" and networked models of the brain flow out of the general PDP approach.

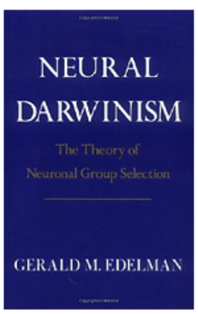


4. Models from Darwinian Theory & Evolutionary Psychology

See excellent Wikipedia article <https://en.wikipedia.org/wiki/Evolutionary_psychology> on the general issue of evolutionary psychology

A. NEURAL DARWINISM (NEURONAL GROUP SELECTION)

- In 1978 Nobel prize-winning biologist, Gerald Edelman (1929-2014), proposed a theory of "neuronal group selection" (usually called Neural Darwinism) in order to explain how the nervous system of humans develops across the lifespan (Edelman & Mountcastle, 1978). He expanded upon this theory in 1987 in his book *Neural Darwinism - The Theory of Neuronal Group Selection*. Edelman put a great deal of emphasis upon the plasticity of the brain. He argued that the world we encounter after birth is not labeled and the brain must figure out what it is experiencing. Thus, it needs to be capable of dealing with a very wide range of possible experiences as well as being flexible enough to respond to what it encounters.

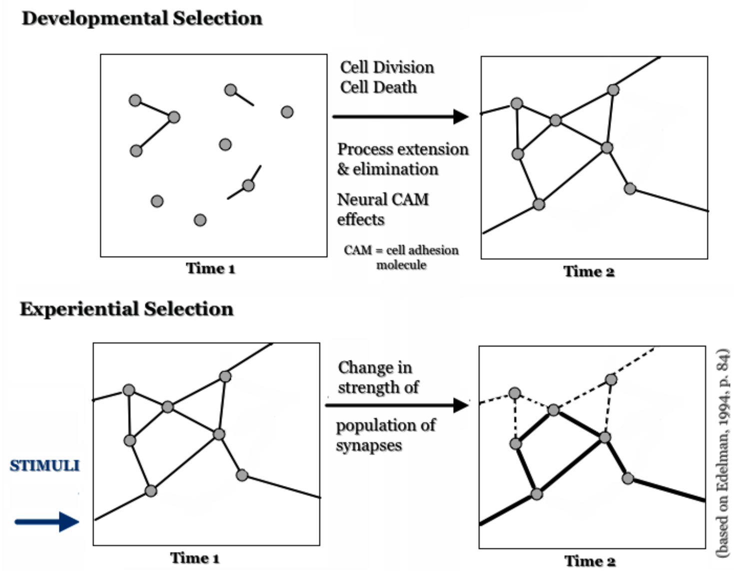


- "At its heart [of Edelman's theory] is the realization that the brain is very different from a computer: as he put it, brains don't work with 'logic and a clock'. Instead, Edelman emphasized the rampantly 're-entrant' connectivity of the brain, with massively parallel bidirectional connections linking most brain regions" (Seth, 2014, para. 4)

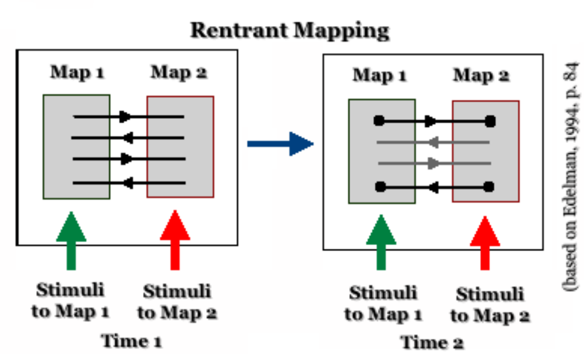
- The theory proposes that three general processes control the development and functioning of the human brain. These are

  - *Developmental selection processes*. Rather than have an exact blueprint of how the brain should be wired, our genes create a more general overall pattern of development in the brain. Certain genes establish a general principle that neurons in area A should connect with neurons in area B, but not which individual neurons should connect with other individual neurons. So, before and immediately after birth our brains create far more neurons and connections than we actually need. In this early developmental period, the neurons and their processes (synapses & dendrites) grow and connect with each other as they follow the effects of the multiple cell adhesion molecules (CAMs) on their surfaces. Neurons that find themselves without connections will die out while those with connections will thrive and sprout even more connections. Selection during the earliest points in development is very much the result of mechanochemical events. In this earliest period of development the brain creates what Edelman describes as the "primary repertoire (repertory)" of neural circuits.

- *Experiential selection processes*. Both before and, especially, after birth, young infants experience a world filled with sensations The baby's nervous system tries to make sense or bring order to what it is experiencing in the many sensations coming both from outside and inside its body. Edelman argues that during the course of early development, the connections in those circuits or neural groups which are most affected by stimuli, that is, are the most used, get strengthened while those connections which go unused essentially wither away. Experience *prunes* or *carves* out in the brain circuits those that are most useful and keeps them. If a circuit is not useful, it will be eliminated. This process of selection leads to what Edelman calls the brain's "secondary repertoire". You may be familiar with the example of an infant's sensitivity to spoken sounds. Research shows that young infants have an ability to hear and discriminate between any sounds produced in human speech. However, after about a year of listening to the speech sounds of the language around them (such as English or Hindi), children can no longer discriminate the sounds made in other unfamiliar languages. In the neuronal selection model, it seems that the connections involving the perception of unused or unfamiliar spoken sounds no longer remain wired in the brain (e.g., Werker & Tees, 1984).

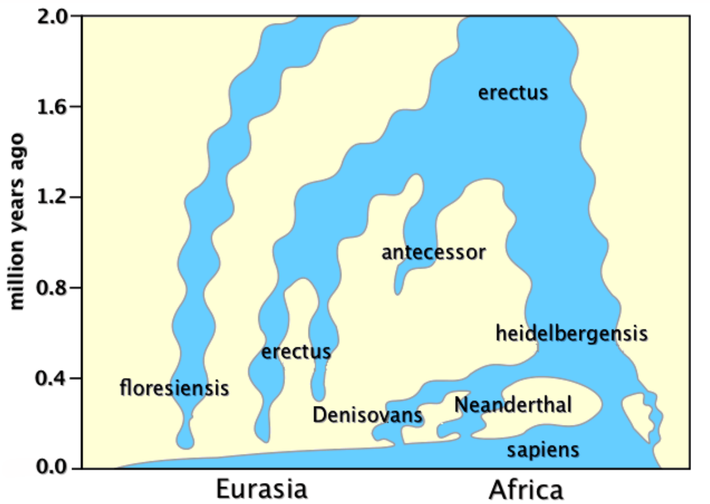


- *Reentrant mapping*. As development continues, the brain must establish multiple maps (bidirectional connections) between sensory and other neural groupings. "These maps are connected by massively parallel and reciprocal connections. The visual system of the monkey, for example, has over thirty different maps, each with a certain degree of functional segregation (for orientation, color, movement, and so forth), and linked to the others by parallel and reciprocal connections. Reentrant signaling occurs along these connections. This means that, as groups of neurons are selected in a map, other groups in reentrantly connected but different maps may also be selected at the same time." (Edelman, 1994, p. 86). In a later reference he explains, "Reentrant neural processes involve the simultaneous exchange of signals in a coordinated manner among multiple dispersed neuronal populations...reentrant processes will be more precisely defined as those that involve one localized population of excitatory (i.e., glutamatergic) neurons simultaneously both stimulating, and being stimulated by, another such population." (Edelman & Gally, 2013, p. 1). A particularly well-documented example of reentrant connections in the brain occurs between the cortex and the thalamus. And, while it is beyond the purposes of this set of notes, Edelman's arguments for reentrant brain processes underlies his theory of how consciousness arises in the human brain.



B. MASSIVE MODULARITY HYPOTHESIS (MMH)

- The human brain as a whole is the result of the process of natural selection operating upon early hominins [1] (= humans and human ancestors [see footnote]) who lived in the environment of evolutionary adaptation (EEA). The EEA for the genus *Homo* corresponds roughly to the stretch of time between 1-2 million years before the present and 10,000 BC (when humans began to gather in small towns). It is believed that our species, *Homo sapiens*, arose ca. 200,000 years ago.

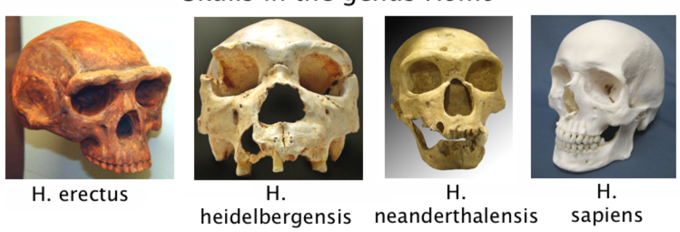


Schematic representation of the emergence of *H. sapiens* from earlier species of *Homo*. The horizontal axis represents geographic location; the vertical axis represents time in millions of years ago. Blue areas denote the presence of a certain species at a given time and place. Early modern humans spread from Africa across different regions of the globe and interbred with other descendants of *Homo heidelbergensis*, namely Neanderthals, Denisovans, and unknown archaic African hominins (bottom right).

Modified from Chris Stringers' hypothesis of the family tree of genus Homo, published in Stringer, C. (2012). "What makes a modern human". Nature 485 (7396): 33–35. doi:10.1038/485033a and released under a Creative Commons license (CC BY-SA 3.0 de) at https://commons.wikimedia.org/wiki/File:Homo-Stammbaum,_Version_Stringer.jpg

- In the EEA, hominins including early *Homo sapiens* (human beings) lived in bands of hunter-gatherers and faced the needs (1) to survive, (2) to reproduce, and (3) to raise their offspring to reproductive age. Gradually many specific adaptations of mental functions and structures arose which permitted these hominins greater success in achieving their needs (survival, finding mates, etc.)

Skulls in the genus *Homo*



"Homo erectus" by Thomas Roche from San Francisco, USA - Homo Erectus. Licensed under CC BY-SA 2.0 via Commons - https://commons.wikimedia.org/wiki/File:Homo_erectus.jpg#/media/File:Homo_erectus.jpg
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- Computational Theory of Mind
    - The brain is ***computational***, i.e., it functions much like a computer does in handling data. The brain is "a computer made out of organic compounds rather than silicon chips. The brain takes sensorily derived information from the environment as input, performs complex transformations on that information, and produces either data structures (representations) or behavior as output" (Barkow, 1992, p. 7 quoted in Samuels, 1998, pp. 577-578)

- The mind is composed of many "***Darwinian modules***" in the brain [Samuels, 1998]

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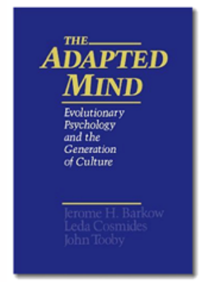
[1] As Wikipedia (20150912) explains, "The *Hominini* is a tribe of the subfamily *Homininae*; it comprises three subtribes: *Hominina*, with its one genus *Homo*; *Australopithecina*, comprising several extinct genera; and *Panina*, with its one genus *Pan*, the chimpanzees. Members of the human clade, that is, the *Hominini*, including *Homo* and those species of the australopithecines that arose after the split from the chimpanzees, are called *hominins*.

- ***Domain-specific*** rather than domain-general cognitive structures (Samuels, 1998, p. 578). These structures are dedicated to resolve problems from limited domains.
- Structures are ***innate***, i.e., almost completely determined by genetic inheritance (and arise from processes of natural selection, see Neural Darwinism below)
- Such modules are ***found universally across the human species*** and, thus, the human mind is generally designed in an identical way across all people.
- Each module processes data either via ***specialized neural structure***s (i.e., hardwired neural computation) or via "s***pecialized mental programs or algorithms***" (Samuels, 1998, p. 580).
- The MMH argues against the brain as showing strong evidence of central processing. (Bermudez, 2014)

• The mind is composed of a **vast number** of such Darwinian modules. Here's how Tooby & Cosmides (1995) the major advocates for this notion, describe them:

Leda Cosmides & John Tooby



> We inhabit mental worlds populated by the computational output of battalions of evolved, specialized neural automata...each of the neural automata...is the carefully crafted product of thousands or millions of generations of natural selection, and each makes its own distinctive contribution to the cognitive model of the world that we individually experience as reality. Because these devices are present in all human minds, much of what they construct is the same for all people, from whatever culture (p. xii)...our cognitive architecture resembles a confederation of hundreds or thousands of functionally dedicated computers (often called modules) designed to solve adaptive problems endemic to our hunter-gatherer ancestors. There are specialized systems for grammar induction, for face recognition, for dead reckoning, for construing objects, and for recognizing emotions from the face. There are mechanisms to detect animacy [*i.e., that something is alive*], eye detection, and cheating. There is a 'theory of mind' module, and a multitude of other elegant machines." (pp. xiii-xiv, italicized comment added).

5. Predictive Coding (Bayesian) Model (Karl Friston, Andy Clark, et al.)

A. THOMAS BAYES (CA. 1701-1761) AND BAYES' THEOREM

Thomas Bayes (b. ca. 1701-1761)

Thomas Bayes, the British statistician and Presbyterian minister, is best known today as the author of ***BAYES' THEOREM*** in statistics. The theorem itself was only published after Bayes' died and it took a while before mathematicians put this theorem to work.

At the heart of Bayes' theorem lies the notion that **the probability of an event happening can be predicted more accurately if we take into account some factor for which we already know the probability. So, for example, if I want to predict whether John is going to arrive on time for his appointment, it helps to know that, in the past, John has been late 50% of the time. Similarly, if I want to know whether a 55-year-old woman, Mary, might die of heart disease, I can use data about the risks of dying of heart disease among other 55-year-old women, in order to make a prediction about Mary's health.**

The formal simple statement of Bayes' Theorem in statistics where A & B are events is

$$P(A \mid B) = P(A) \cdot P(B \mid A) / P(B)$$

Or, in words, the probability of A given that B is true is equal to the probability of A times the probability of B given A is true divided by the probability of B. Having stated this I will leave the statistical details for someone else to explain since the math is not crucial for what follows below.

B. PREDICTIVE CODING IN THE BRAIN

http://safety.fhwa.dot.gov/roadway_dept/horicurves/fhwasa07002/images/image017.jpg

Imagine what it is like as you are driving a car and you come to a curve in the road. How do drivers handle the task of turning the car in such a way that it stays in lane, but negotiates the curve as well?

According to the findings of neuroscientists, engineers, and others who study what happens when you are driving, there is a clear process involved. Rybarczyk and Mestre (2012) explain: "Studies on the direction of a driver's gaze while taking a bend show that the individual looks toward the tangent-point of the inside curve. Mathematically, the direction of this point in relation to the car enables the driver to predict the curvature of the road. In the same way, when a person walking in the street turns a corner, his/her gaze anticipates the rotation of the body" (p. 1). The figure below illustrates what they are describing:

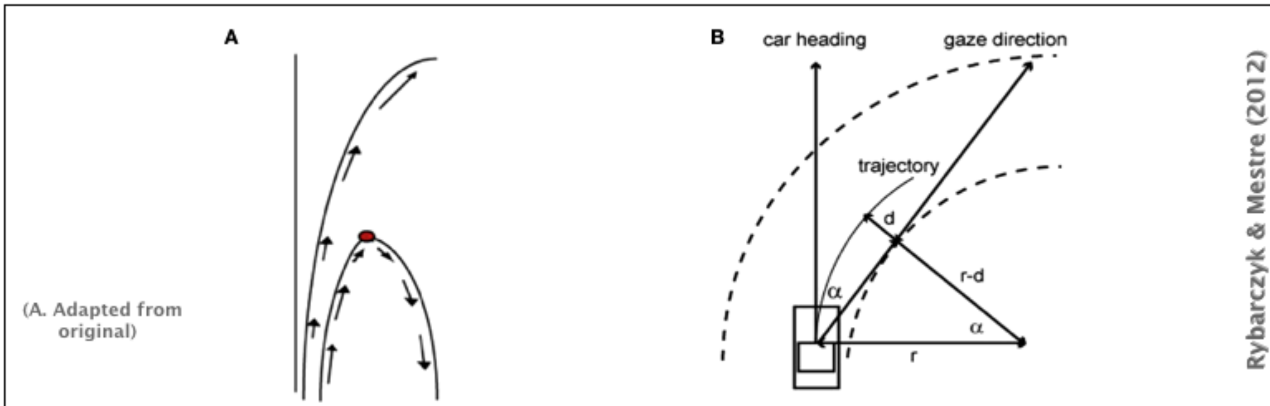


FIGURE 1 | (A) The tangent-point of the inside curve is visually immobile in the dynamic visual field of the observer. **(B)** When the driver's trajectory follows the bend, looking toward the tangent-point provides a prediction of the road curvature (after simplification, $1/r = \alpha 2/2d$).

Even more specifically, they note, ""Land and Lee (1994) demonstrated that, while driving an automobile, humans invariably fixate their eyes near the point of maximum curvature, along the road ahead, approximately 1–2 s prior to reaching the curve and maintain their gaze relatively fixed on that point while bending. The reason why the driver looks toward the tangent-point of the inside curve is because of the singular optical properties of this part of the road. Indeed, at this specific point there is a reversion of one of the components of the optical flow, which maintains an identical position in the visual field for a constant curvature and, consequently, makes this location particularly relevant to stabilize the vehicle's trajectory (Kandil et al., 2009). A simple mathematic relationship shows that this stable cue can be used by the driver to predict the curvature of the road" (Rybarczyk and Mestre, 2012, p. 1)

So what? I am citing this example to introduce what is called the "predictive coding" or Bayesian model of the brain.

According to this model, the human mind is not a passive computer waiting for data to process and then respond with some action. The Luria model involving what Park et al. (2012) term "traditional *perception-to-cognition-to-action* strategies" (p. 1, emphasis added) is too simple and, indeed, far too slow. As they argue:

> Individual neurons encode/decode information at < 10^3 Hz, yet, in less than 200-300 ms, complex visual objects are recognized. [And, in this short period] our brain somehow manages to clean up the noisy spatio-temporal fluctuations of incoming photons on the retina, encode key information embedded within such fluctuations in the language of spike trains, relay them to dozens of more specialized high-order visual areas, extract invariant features using mysteriously judicious neuromorphic machine learning algorithms, and finally bind the distributed features into a uniform percept which lets "us" feel the quality of the perceived object (p. 1)

The chief theorist of predictive coding, Karl Friston, is a physician and neurobiologist who teaches at University College, London and is the Scientific Director of the UK's Wellcome Trust Centre for Neuroimaging. He had earlier in the 1990s developed the statistical methods necessary to analyze three-dimensional MRI images (that is, *voxel-based morphometry*) and then went on to invent *dynamic causal modeling* in order to understand the architecture of dynamic systems in the brain and other distributed system phenomena (see Wikipedia summary). When he turned his attention to predictive coding, Friston (2009) introduced the notion in this fashion by describing the brain as "prophetic":

Karl Friston

> The **commonly held belief** that information from the outside world impinges upon our brains through our senses to cause perception and then action **now appears to be false**.
>
> Over the past decade, neuroscience has revealed that rather than acting as a filter that simply maps sensation onto action, the brain behaves like an "inference machine" that tries to discover patterns within data by refining a model of how those patterns are likely to be generated. For instance, depending on whether the context is a crowded concert hall or a deserted forest, a sound can be perceived as either a human voice or the wind whistling through trees. The pioneering German physicist Hermann von Helmholtz articulated this idea as early as 1860, when he wrote of visual perception that "objects are always imagined as being present in the field of vision as would have to be there in order to produce the same impression on the nervous mechanism." Now a unified understanding of how the brain makes and optimizes its inferences about the outside world is emerging from even earlier work—that of the 18th-century mathematician Thomas Bayes. (para. 1)

Andy Clark, both a philosopher and cognitive neuroscientist now at the University of Edinburg (whose Twitter feed is "Fluffycyborg"), is well-known for his work on the "extended brain" hypothesis along with David Chalmers. Clark is a notable proponent of predictive coding theory and in 2011 clarifies the notion:

Andy Clark

> "The basic idea is simple. It is that to perceive the world is to successfully predict our own sensory states. The brain uses stored knowledge about the structure of the world and the probabilities of one state or event following another to generate a prediction of what the current state is likely to be, given the previous one and this body of knowledge. Mismatches between the prediction and the received signal generate error signals that nuance the prediction or (in more extreme cases) drive learning and plasticity." (para. 3)

A third way of describing what happens comes from Brown et al. (2011):

> "Predictive coding is based on the assumption that the brain makes inferences about the causes of its sensations. These inferences are driven by bottom-up or forward sensory information that is passed to higher brain areas in the form of prediction errors. Top-down or backward connections convey predictions that try to suppress prediction errors until predictions are optimized and prediction error is minimized" (p. 2)

The basis of predictive coding is, thus, two-fold: (1) based on experience, the mind creates (learns) multiple internal models of the external world, i.e., internal expectations of what the individual can expect when interacting with the world and (2) "top down" predictions about the content of incoming stimuli which minimize "surprise" at what we encounter. Hence, the mind is using two distinctive mechanisms in order to understand what it experiences: (A) "prediction error rather than incoming raw data as the fundamental currency of the brain's *information processing*" and (B) an "*information interpretation* system that assigns a cause ("belief") to the observed prediction error" when what is expected either does or does not happen (Park et al., 2012, p. 1).

Prediction Errors (PEs). A prediction error can be defined as "the mismatch between a prior expectation and reality. Prior expectations are based on an agent's model of the world, which is partly hard-wired in the structure of the neural circuits and partly derived from statistical regularities in the sensory inputs that the agent experiences over a lifetime" (den Ouden et al, 2012, p. 2). Two types of PEs are

- *Perceptual & Cognitive* PEs "which report the degree of surprise with respect to a particular outcome"
- *Motivational* PEs "which also report the valence (sign) of a PE, i.e., not only whether the outcome was surprising but also whether it was better or worse than expected." (den Ouden et al, 2012, p. 2)

A Background Note. In 1948, the Bell Labs scientist, Claude E. Shannon, published his groundbreaking two-part study, *A Mathematical Theory of Communication*. In this work, Shannon argued that *information* itself ultimately is equivalent to a reduction of the uncertainty or surprise that an organism experiences. If I meet you and you don't know me, when I tell you my name, I have reduced the uncertainty you have about me. Often enough, in order to be sure that an accurate message is communicated from one person to another, the communicator will employ multiple channels in order to get the message across accurately, for example, speaking words slowly while using hand and facial gestures that also convey the meaning of the message. Or, at a convention, a person might wear a name badge and, at the same time, introduce themself to someone else. Redundancy is a frequent characteristic of messaging systems.

Claude Shannon

Lisa Feldman Barrett's (2020) model of the brain is grounded in the predictive coding model (with an acknowledgment of evolutionary theory as well). We do not have brains "to think." Rather, brains evolved to manage the energy needs of the whole organism. Barrett calls this "body [energy] budgeting. As she argues,

> "When it came to body budgeting, prediction beat reaction. A creature that prepared its movement before the predator struck was more likely to be around tomorrow than a creature that awaited a predator's pounce. Creatures that predicted correctly most of the time, or made nonfatal mistakes and learned from them, did well. Those that frequently predicted poorly, missed threats, or false-alarmed about threats that never materialized didn't do so well. They explored their environment less, foraged less, and were less likely to reproduce." (p. 10

Lisa Feldman Barrett