2 Overview of the Brain

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The HUMAN BRAIN COLORING BOOK
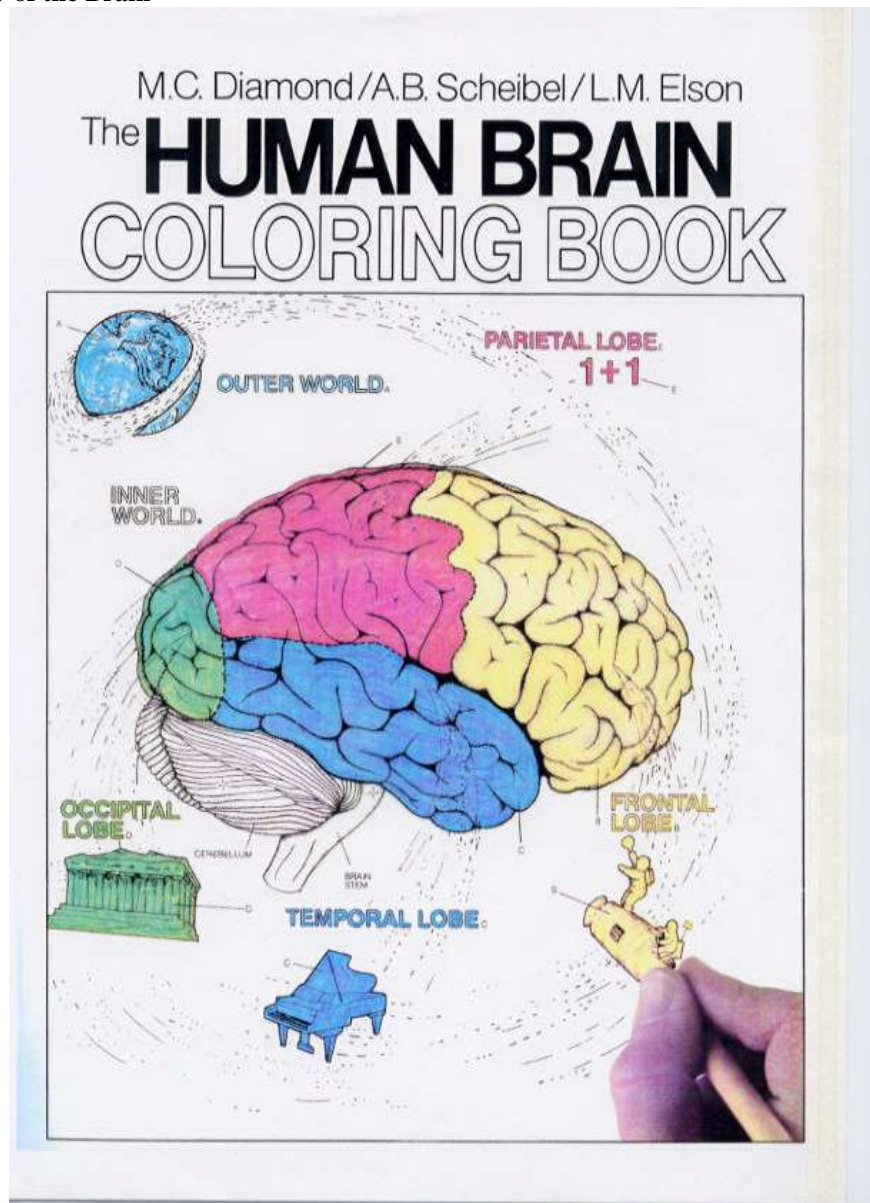
2.3 What is the brain ?

- Vast collection of interconnected cells called neurons.
    - 10^{12} neurons with 10^{15} synapses (connections)
    - cortical neurons connect to roughly 3% of surrounding neurons
    - cortical neuron may receive connections from up to 10000 other neurons

- "Supported" by an even greater number of cells called glia (not nerve cells!)
- Many different types of neurons in terms of size, shape and molecular properties (12 general types in the neocortex). Each neuron has three distinct parts:
    1. cell body (soma) - can be the site of input, mainly inhibitory
    2. dendrites - input zone
    3. axon - output pathway
- Neurons are connected together in particular ways to form functional circuits, much like transistors, resistors and capacitors are connected to form electronic circuits.
- Neurons communicate via electrical impulses called action potentials

- o there are other forms of communication as well e.g. gap junctions
- Effect (via an action potential) of one neuron on another can be
  - o excitatory - encouraging the receiving neuron to emit an action potential
  - o inhibitory - discouraging the receiving neuron from emitting an action potential.

2.4 The parts of the brain

The Brain: Organ of the Mind
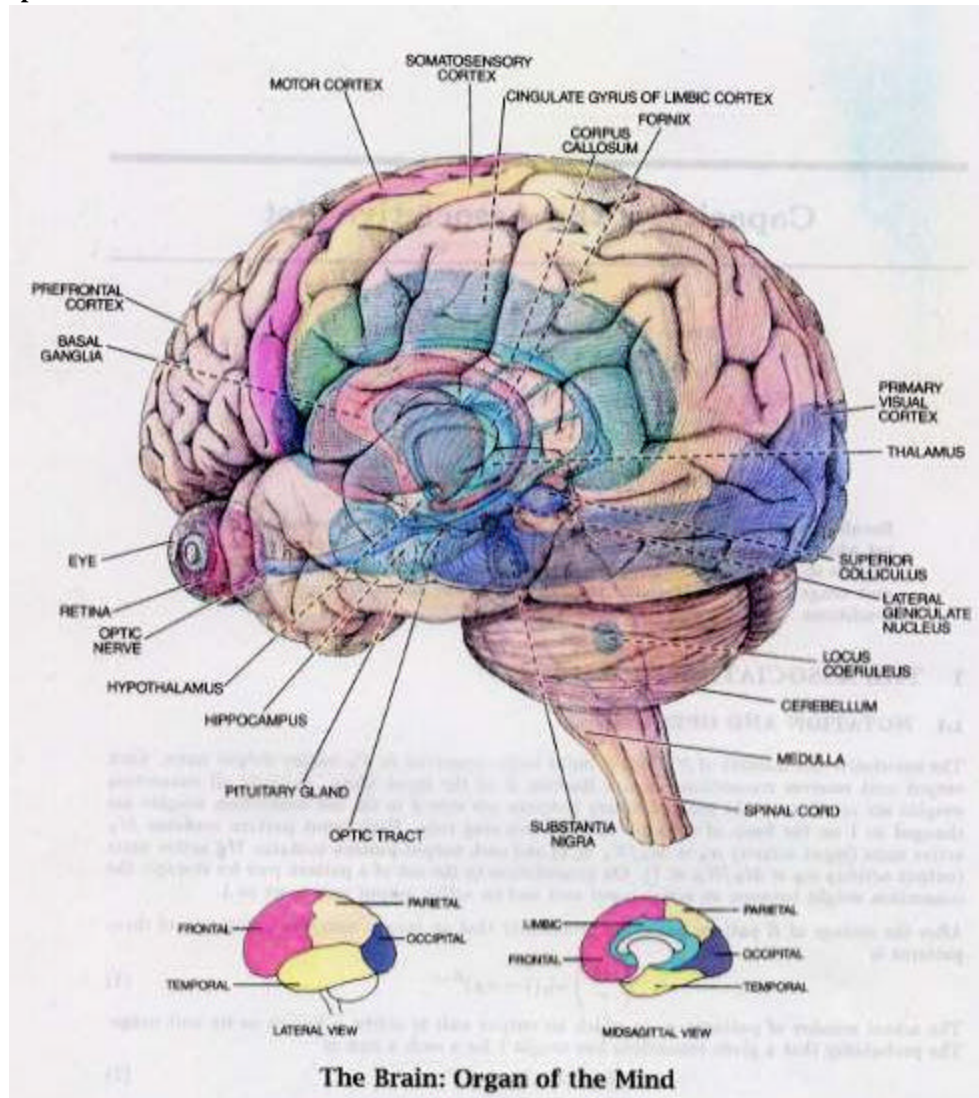
[Scientific American, September 1992]

- Spinal cord
  - o signals to and from the muscles travel to the brain via the spinal cord
  - o also sensory signals for touch, temperature, pain etc (somatosensory signals)
  - o cord consists largely of axons conducting information from sensory cells to the brain, and information from the brain to motor neurons that drive muscles
  - o cord also contains a large number of neurons, both motor neurons and interneurons
  - o much processing takes place locally in the spinal cord giving rise to what we call reflexes
- Brain stem
  - o "half-way house" through which passes all sensory information on its way to the brain, including visual and auditory information (but not olfaction)
  - o the main "way station" is the thalamus
  - o much low-level (unconcious) processing takes place here
- Cerebral Cortex
 - o sight of all high level processing

- o layers of neurons (grey matter) and large tracts of connections between neurons (white matter - myelinated axons)
  - o comes from the Latin word for bark
  - o upper surface of the cerebral cortex consists of a layer of grey matter about 3-5mm thick, comprising six identifiable layers of neurons, dendrites and axons
  - o it would cover an area of about $1.5m^2$ if laid out flat
  - o evolutionarily older parts of cortex, such as the hippocampus, have a simpler structure
  - o isolated pockets of grey matter beneath the surface known as the basal ganglia that receive signals from many parts of the cortex and send signals back principally to the motor cortex
  - o divided into two hemispheres connected by a large bundle of nerve fibres called the corpus callosum
  - o surface divided into four areas known as temporal, occipital, parietal and frontal lobes
- Cerebellum
  - o sits beneath the cerebral cortex at the back of the brain
  - o very regular and simple structure
  - o highly folded cortical surface of grey matter with deeper nuclei of grey matter, all connected via white matter, much like the cerebral cortex
  - o something to do with the control of coordinated movements
  - o very high level of information processing as almost 40 times as many axons enter the cerebellum as leave it

2.5 Development
- Brain grows at 250,000 cells a minute in the foetus.
- Full complement of neurons at birth and no new neurons formed after this. Many neurons die each day!
- Considerable development after birth involving the formation and refinement of connections between neurons. Growth of dendrites and synaptic spines.
- Development relies on interaction with the world. Appropriate sensory information is essential to the normal development of the brain. For example, deprivation of visual stimuli distorts development of the visual system during the crucial period of a few months after birth.
- While most development ceases after the first couple of years, we retain the ability to remember facts and learn new skills throught our lives. Perhaps the most remarkable feature of the brain is its plasticity.

2.6 Functional view
- Sensory input $\Rightarrow$ Central systems $\Rightarrow$ Motor output
- Sensory input: vision, hearing, touch, smell, etc
- Motor output: limbs, eyes, mouth, etc
- Central systems: thinking, memory, language, voluntary movement, perception (vision, hearing, smell etc)
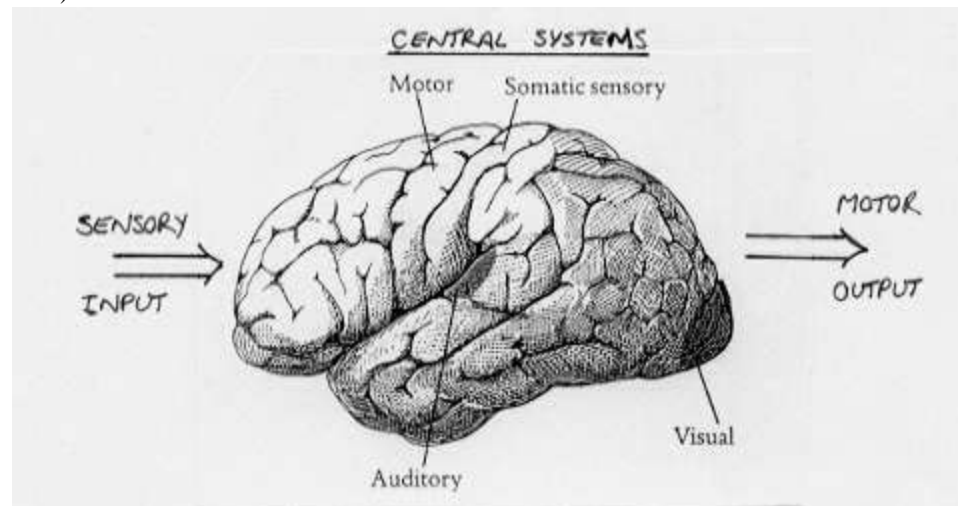
- Functional specialisations in cortex
  - sensory inputs arrive in particular areas of cortex, so we can speak of visual cortex, auditory cortex, somatosensory cortex
  - inputs map onto the cortex in a topographic way e.g. somatosensory input from particular parts of the body map to particular parts of cortex so that we can draw a map of the body on the cortex
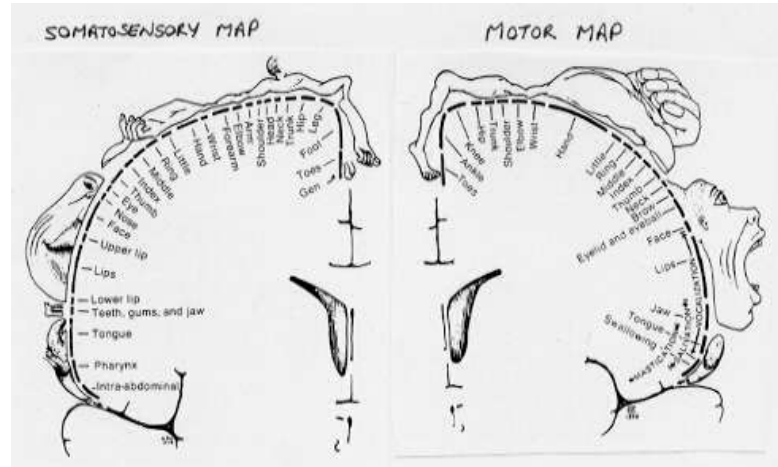

  - inputs from the right half of the sensory field go to the left half of the brain and vice versa
    - left half of the visual field, as seen by both eyes, goes to the right half of the brain and vice versa
    - sound from both ears goes to both sides of the brain to aid in sound localisation
  - motor outputs also map to the body, with the left half of the body being controlled by the right half of the brain and vice versa
  - areas that are not specialised for particular inputs or outputs are known as association areas
    - reading, writing and arithmetic
    - largely localised to one side of the brain or the other
    - these areas are greatly expanded in humans, reflecting our enhanced cognitive abilities
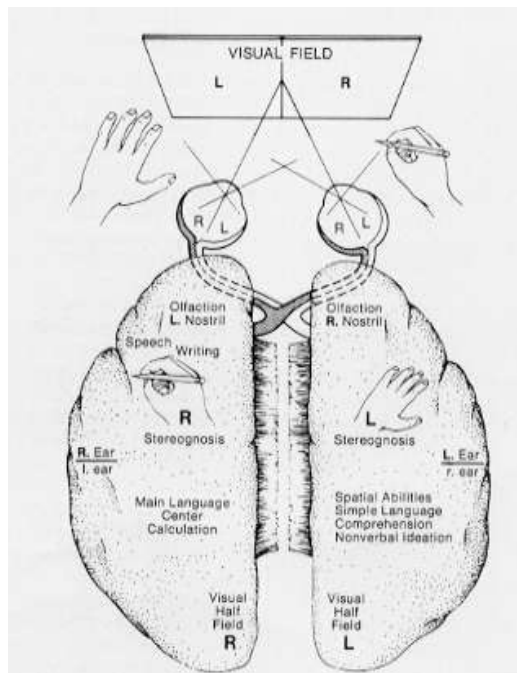

[SH88 Fig. 30.16 pg 635]

- Levels of processing
  - processing of sensory input or generation of motor output involves many different areas of the brain, with each area carrying out one part of the task
  - the flow of information through the brain can be mapped for different tasks
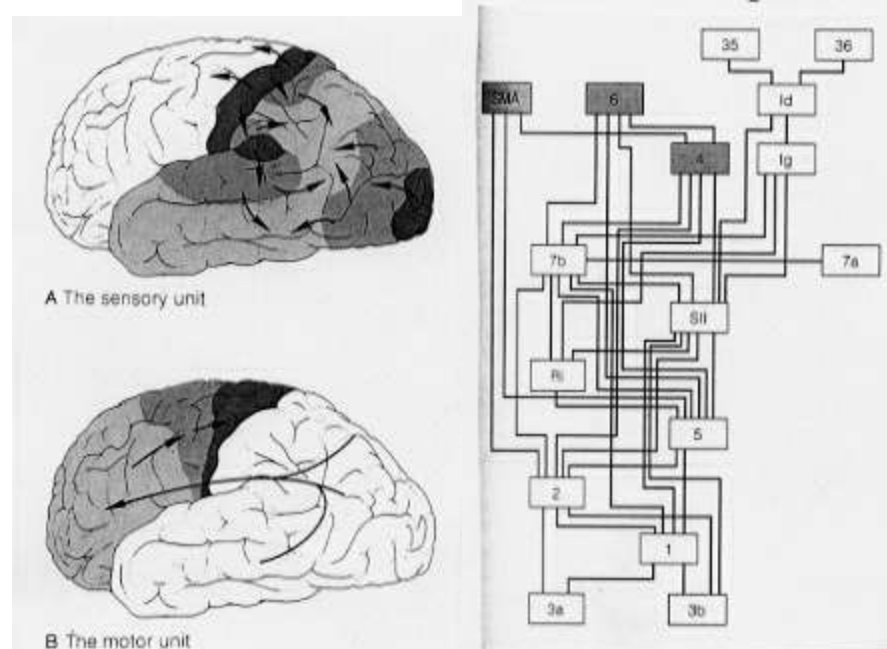
[KW96 Fig. 8.10 pg 170; Fig. 8.13 pg 175]
  - hierarchies of processing exist, but the flow of information is never strictly feedforward
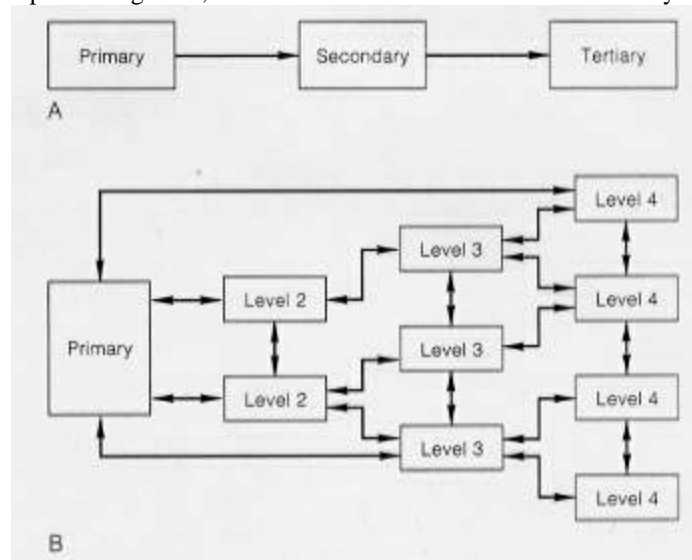
[KW96 Fig. 8.11 pg 172]

2.7 What happens when things go wrong
- Anterograde amnesia: cannot remember anything AFTER the time of the injury for more than a few minutes i.e. existing long-term memories are intact, short-term memory is intact, but cannot lay down new long-term memories
- Inability to recognise faces: may easily recognise someone by their voice or other cues, but not by looking at them
- Severing the corpus callosum: person can only name an object (key, coin etc) if it is placed in their right hand (information can reach the language centres in the left hemisphere) but not in their left

hand (information reaches conciousness in the right hemisphere, but cannot cross over to the left hemisphere).

2.8 Places to start
- Shepherd (1994) Neurobiology, Chapt. 1: Introduction
- Brodal (1992) The Central Nervous System, Chapt. 2: The different parts of the nervous system
- Churchland and Sejnowski (1992) The Computational Brain, Chapt. 2: Neuroscience overview
- Diamond et al (1985) The Human Brain Coloring Book

The structure of neocortical circuits.

Introduction.

The mammalian cortex exhibits a highly specific neuronal architecture which includes both intrinsic recurrence at a local-circuit level, and extrinsic reentrance between areas in a hierarchical structure (Braitenberg, 1977; Braitenberg and Schuz, 1991). This architecture does not exist in sub-mammalian vertebrates, but may have arisen through the integration of the reptilian dorsal ventricular ridge and the primordial pallium of the reptilian telencephalon (Deacon, 1990; Karten and Shimuzu, 1989).

The ubiquitous presence of reentrant projections from later to earlier hierarchical areas of the cortex, at comparable densities to the forward axonal projections has been widely noted (for a review, see Felleman and Van Essen, 1991). These reentrant connections carry a vast flow of information in the "top-down" as well as the "upward" direction through the processing hierarchy. In general, the lowest levels of this hierarchy, in the sense of their proximity to primary sensory input, are located in highly differentiated and somewhat specialized areas of the occipital (visual), temporal (auditory) and parietal (somatosensory) neocortex, while the highest levels are apparently located in the limbic system and in areas of the prefrontal, temporal and parietal lobes which are closely associated with the limbic system (Pandya et al., 1988). Local recurrent circuits are created by the interconnections of local axonal ramifications with basal dendritic trees of pyramidal cells, as well as possibly the connections created by Martinotti cells and stellate cells (White, 1989). In this page, the term "reentrance" is used specifically to describe the pattern of topographically mapped, direct and inverse connections between cortical areas, while the term "recurrence" refers to local circuit connections which link proximate cells into a dense web. Mumford (1991, 1992, 1994) has suggested that the layered structure of the cortex, in conjunction with the pattern of forward and reentrant projections between retinotopically mapped areas (as well as projections to thalamic nuclei) could constitute a suitable architecture for solving pattern-theoretic problems in general, and specifically problems involving Bayesian inference. In Mumford's view, information processing in the cortex may involve an optimization process comparing an internally generated model to an externally driven transformation of sensory data, within the context of an a priori (learned) set of parameters and constraints stored within the network of synaptic interconnection weights.

Cortical cell types.

A wide variety of cell types has been noted in the neocortex. However, all of the cells may be broadly divided into two categories: those which are presynaptic to excitatory (Type I, asymmetrical) synapses, and those which are presynaptic to inhibitory (Type II, symmetrical) synapses. The excitatory cells include the pyramidal cells and the spiny stellate cells. According to Braitenberg and Schuz (1991), these two types account for about 85% of the cells in the cortex, and approximately 75% of all synapses in the cortex are between cells in this category. Pyramidal cells are more predominant than spiny stellate cells: White (1989) estimates that 70-80% of the neurons in neocortex are pyramidal cells. The pyramids are characterized by their apical & basal dendrites and by an axon which projects vertically out of the cortical gray into the white matter below. Pyramidal cells typically receive inhibitory synapses on their cell bodies, and excitatory synapses at their dendritic spines.

The spiny stellate cells are considered by both Braitenberg & Schuz and White to be part of a continuum with pyramids. However, the spiny stellate cells are smaller, and generally lack a long main projection axon. They are considered to be primarily a type of local circuit neuron. (White identifies a third type of excitatory neuron, which he calls the first type of double bouquet cell;

however, the distinction between the double bouquet cells and spiny stellate cells is not made entirely clear.)

The inhibitory cells include Braitenberg's non-spiny stellate cells (presumably including White's chandelier cells, basket cells, and the second type of double bouquet cells) and Martinotti cells. Chandelier cells are characterized by axons which terminate on initial axon segments of pyramidal cells. Basket cells have dendrites which ramify in the immediate vicinity of their cell bodies, but their axons may travel horizontally into adjacent functional column before synapsing on axon hillocks and cell bodies of pyramids. Their axon boutons form inhibitory nests around pyramid bodies. The second type of "double bouquet" cells has an axon which ramifies beneath its dendritic tree. Martinotti cells have very compact dendritic arborizations, and have an ascending main axon which typically reaches layer I of the cortex.

The neocortex is approximately 1-4 mm thick and is often described as consisting of six layers. The layers were initially distinguished on the basis of their appearance in Nissl stained sections, which is primarily sensitive to the density and size of neural cell bodies. Layer I, the "plexiform" layer (closest to the pial surface) has few cell bodies, and consists almost entirely of axonal and dendritic ramifications. Layer IV consists predominantly of densely packed spiny stellate cells (also known as "granular" cells), with an accompanying absence of pyramidal cells. This layer is most evident in the primary sensory areas of the cortex (where it may have several distinguishable sublaminae) while it is nearly absent in motor areas. Layers II and III contain many pyramidal cells. Layer II is distinguished from layer III by its slightly smaller cell bodies; however, Braitenberg argues that this is essentially a continuum, with the smaller size of the layer II pyramids possibly accounted for by the smaller size of the dendritic arborization required to reach layer I. Similarly, layers V and VI contain pyramidal cells which tend to be larger in layer V, while the cell bodies of layer VI may be more irregularly shaped than those of layer V; but functionally layers V and VI may essentially represent a continuum. This viewpoint is adopted by Felleman and Van Essen (1991), who (in their survey of the literature on cortico-cortical connections by layer) view the cortex as functionally consisting of three layers: a supragranular layer (including layers I, II and III), a granular layer (layer IV) and an infragranular layer (layers V and VI.) However, a counterindication is that for LGN stimuli, monosynaptic EPSP's occur in layers 3-5, while layers 2 and 6 typically show disynaptic EPSP's. (Toyama et al., 1974, cited in White, p. 143).

The pattern of connections in the cortex may be analyzed in two groups. These are the the extrinsic (global) circuits and intrinsic (local) circuits. Braitenberg (1977) refers to these circuits as the A-system and the B-system, respectively.

Local cortical circuits.

The intrinsic (B) system is highly complex. There may be a tendency for cells in the infragranular layers to send local axonal collaterals to the supragranular layers, and conversely; but some collaterals also occur in the same layers as the cell bodies of their origin. These collaterals generally ramify in the immediate horizontal vicinity of the cell body, but they sometimes travel long distances horizontally before ramifying. Deep pyramidal cells (layers V-VI) have apical dendrites ramifying in layer IV and above, while cells of layers II and III ramify in layers I, II and III only. Within a layer, sub-populations of pyramidal cells may sometimes be identified by the layers of ramification of their apical dendrites, and also by the targets of their axons. Usually, basal dendrites ramify within the same layer as the cell body, but there are exceptions: layer 4a cells of monkey V1 basal dendrites ramify in 4b, avoiding 4a. Spiny stellate and local plexus (local circuit) neurons occur primarily in layer IV. Inhibitory interneurons are found in all layers of the cortex. The function of inhibitory interneurons is evidently to balance the predominance of excitatory interactions in the pyramidal system, to prevent runaway activation due to positive feedback. Activation levels of inhibitory neurons in a cortical region may tend to be highly correlated with the activation levels of excitatory neurons in that same region. Some connections of the intrinsic (B) system are illustrated in figure 1.

Figure 1. Intrinsic (B) circuits of the neocortex. Note dense interconnections between basal dendrites and local ramifications of projection axons in both supragranular and infragranular layers; and connections between supragranular and infragranular layers mediated by local plexus cell and local ramification of supragranular axon.

Global cortical circuits.

The extrinsic (A) system is also highly complex, but its connections reflect the hierarchical organization of cortical areas in the sensory and motor processing streams. Pandya, Seltzer and Barbas (1988) state that forward projections in the cortex generally originate in layer III and terminate in layer IV, while reentrant projections originate in the infragranular layers (V and VI) and terminate in layer I. A third class of interconnections is diffuse in both origins and terminations. Felleman and Van Essen (1991), in a survey of some 52 tracer studies of cortical connections in monkey cortex, found a somewhat more complex picture. They found that some ascending and descending connections (especially higher in the sensory hierarchy) exhibit bilaminar origins (from both supragranular and infragranular layers), and that most or all descending (feedback) projections ramify in both supragranular and infragranular layers. They confirmed that ascending projections terminate primarily in the granular layers. The structure of extrinsic cortico-cortical connections is shown in figure 31.

The extrinsic system also includes projections to and from extra-cortical structures. Typically, sensory projections and other thalamic projections terminate in layer IV, while projections from the cortex to thalamic, striatal and spinal targets originate in the infragranular layers (V and VI). Extrinsic cortico-cortical connections tend to occur between distinct cortical areas, which may be mapped either by cytoarchitectonic criteria or electrophysiological criteria. With few exceptions, these maps generally tend to coincide. Cytoarchitectonic areas are determined by cortical thickness; number and thickness of layers; sizes, shapes, types, density and dispositions of cells; and staining properties. Some borders are sharp, others gradual. Some areas are preserved across species, but may vary greatly in size even from individual to individual. Cell density is nearly constant except in area 17 (the primary visual cortex), which is twice the density of other areas. GABA (inhibitory) neurons are 25% of neurons in all areas except area 17, which is 20% GABA.

Figure 2. Extrinsic (A) circuits of the neocortex. Note that forward connections tend to originate in supragranular pyramids and terminate in the granular layer, while reverse connections tend to originate in infragranular pyramids and terminate in the plexiform layer.

Computation in cortical circuits.

The cortical structures provide a rich substrate for computational processes including reentrance and recurrence. It is interesting to note that forward connections always terminate in the granular layer, and to speculate that the function of the granular layer may be similar to the function of the error (difference) layer in the negative-feedback process of the BRIAN model.

A possible explanation for the differentiation of cortical layers is that computation in individual cells is based not only on integration of average rates of post-synaptic impulses to the dendritic trees, but also based on relative timing between inputs. Hopfield (1995) suggests that cells with timing sensitivity might function like radial-basis units rather than summing units. This would add significant computational power to the system. If this interpretation is correct, then the thickness of the cortex might facilitate the development of vertically-oriented delay lines of varying length, to provide a basis population for differential selection by a learning process.

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