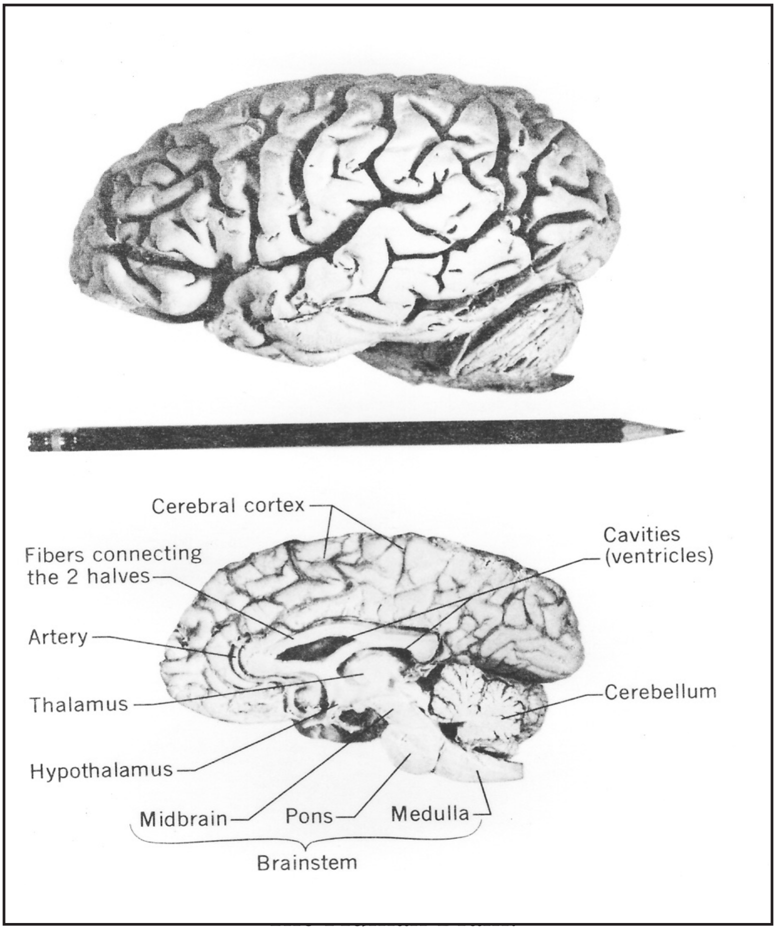
Chapter 1
Overview

Overview Introduction

> *Absolute truth is like a mirage; it tends to disappear when you approach it ... Passionately though I may seek certain answers, some will remain, like the mirage, forever beyond my reach.*
>
> — Richard Leakey and Roger Lewin

Perhaps nowhere in science is this quote more appropriate than in neuroscience. Science has just emerged from the "Decade of the Brain," so called because we believe that a critical mass of information and understanding now exists that tempt us to believe we can understand the great mysteries of brain and mind. Yet our search for full and absolute truth may well prove to be forever beyond our reach.

A beginning point in this search is to ask, "What is a nervous system for?" Plants do not have one, and plant species generally seem to survive just fine. Clearly, a nervous system is not necessary for evolutionary success - at least for organisms that do not move about in their environment. But creatures that move about in their environment have the opportunity to change their environment. That ability allows such organisms to have more options for survival. In short, there are ecological niches for organisms that are flexible enough to change their environment. And that is why those niches have been filled with organisms with nervous systems.



To be able to move about and change the environment, organisms have certain special needs not required by plants. Obviously, they must have a mechanism to move their protoplasm around in the environment, and it certainly helps to have a control system for coordinating movements. Additionally, such organisms need an array of sensors that inform them of the conditions of the environment in which they have the option to move, as well as a processing network that decides whether the environment is optimal or whether "better" conditions should be "sought".

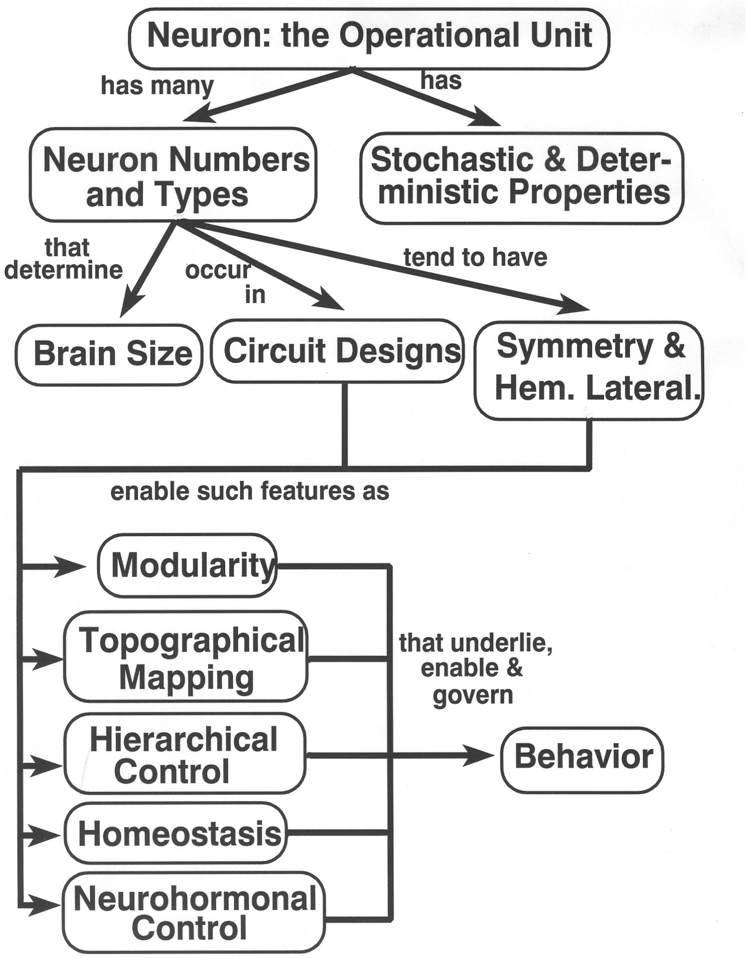
Even the most primitive one-celled animals, such as Paramecia, have some of these capabilities. The evolution of higher life forms could be regarded as Nature's way of evolving more efficient and powerful nervous systems. Indeed a progressive refinement of nervous systems is a major theme of animal evolution, culminating in the extraordinary mental powers of humans.

In this overview category of 12 nervous system core ideas, we begin by identifying the basic operational unit of the system: the **Neuron**. Next, we introduce **Neuron Numbers and Types**, the idea of differing kinds of neurons and the importance of their occurrence in large numbers in the higher animals and humans. Then, we deal with the perplexing issue of **Brain Size**, which seems to be related, but only incompletely so, to the computational power of nervous systems.

Operations of these modules and the units within them paradoxically exhibit both **Stochastic and Deterministic** (random and non-random) properties that give animals a basis for self-generating function as well as a sensitive ability to change function in response to changing conditions. Neurons are organized into a variety of complex **Circuit Designs**, which route information flow. Organization of these circuits tends to have **Symmetry and Hemispheric Lateralization**, yet another paradox in which seemingly incompatible concepts co-exist. We describe how many of these circuits are organized to act with **Modularity** and thus constitute a system of interacting modules.

Then, we discuss **Topographical Mapping**, the idea that much of the world, including an organism's own body, is mapped in the brain. By such mapping, the brain has a way to represent the world within its circuits and a way to issue output commands that are appropriate to that world. Next we identify **Hierarchical Control** in the nervous system, a property that provides efficiency of operation typical of hierarchies in general. But the hierarchical organization of complex nervous systems is adjustable to biological demands, and thus the nervous system can be flexible. **Homeostasis** is a process of servo-regulating control that keeps the various nervous operations in balance. A key to the ability to exert homeostatic control is **Neurohormonal Control**.

The collective influence of these various ideas leads to our last idea in the overview category, **Behavior.** For many purposes, we can regard behavior from a simple mechanistic perspective of patterned activity of glands and muscles.



Concept map for the principles that provide an overview of the nervous system.

Ideas in this Category:

- **Neuron: The Operational Unit**
- **Neuron Numbers and Types**
- **Brain Size**
- **Stochastic and Deterministic Properties**
- **Circuit Design**
- **Symmetry and Hemispheric Lateralization**
- **Modularity**
- **Topographical Mapping**
- **Hierarchical Control**
- **Homeostasis**
- **Neurohormonal Control**
- **Behavior**

List of Ideas

Neuron: The Operational Unit

The basic cellular unit that mediates the information processing actions of the nervous system is the single cell type called a neuron. The essence of neurons can be captured in three words: they are specialized, numerous, and hyperdense in their interconnections. There are other, far more numerous, cells associated with the nervous system. These cells are called "glia," and they provide multiple, but incompletely understood, supporting functions.

Neuron Numbers and Types

Brains have enormous numbers of "computing" elements (neurons) that accomplish sophisticated computation because of their large numbers, extensive interconnections, and their high degree of specialization into different types of neurons. These types vary structurally and in the neurochemical ways by which they interact.

Brain Size

Brain size and neuron number are related to mental and behavioral capabilities, but not always in any clear, simple, or linear way. In humans, key differences in intellectual competencies seem to correlate with differences in a small number of discrete brain areas, rather than with overall brain size.

Stochastic and Deterministic Properties

The brain is a highly complex system that has both stochastic and nonlinear, deterministic properties. These are big words, loaded with meaning. But they provide a crucial perspective from which to comprehend how the brain operates.

Circuit Design

Neural circuits are organized in certain basic ways: converging, diverging, parallel, and feedback. This provides an anatomical basis for distributed, parallel processing in large networks of neurons.

Symmetry and Hemispheric Lateralization

The brain is basically bilaterally symmetrical, which is a fundamental biological principle of vertebrate structure. Many functions in the brain are not bilaterally symmetrical, but rather are controlled by neuronal groups in one or the other hemisphere. These lateralizations seem to involve mostly higher nervous system functions and seem to be more pronounced with cortical regions of the brain.

Modularity

The nervous system is organized as interacting modular subsystems.

Topographical Mapping

Major sensory and motor systems are topographically mapped. That is, the body, both inside and out, is mapped by the nervous system. Major sensory systems map the external world within their own circuitry. Likewise, the nervous system contains a mapped control over the muscles of the body. Mapped regions may have different inputs or outputs or may share the same ones. Maps are interconnected so that projections from one map to another trigger a back projection to the first map. Mapping can persist at all levels in a given pathway.

Neurohormonal Control

A major function of the nervous system is to release certain chemicals into the bloodstream that act as hormones to regulate various hormone-producing glands.

Hierarchical Control

The nervous system functions as a hierarchy of semiautonomous subsystems whose rank order is variable. There is no permanent "supervisor" neuron or population of neurons. Any subsystem may take part in many types of interrelationships. Whichever subsystem happens to dominate a situation, each subsystem is independent only to a certain extent, being subordinate to the subsystem above it and modulated by the inputs from its own subordinate subsystems and from other subsystems whose position in the hierarchy is ill-determined. This design feature of the mammalian nervous system provides maximum flexibility and is probably the basis for the brain's marvelous effectiveness.

Homeostasis

The brain regulates the bodily internal milieu through coordinated control over hormones and the nerves that supply viscera. The brain also has homeostatic control mechanisms over its own neural circuitry.

Behavior

Behavior is what emerges from the nervous system's output to glands and muscles, particularly muscles. Behavior, in turn, has feedback actions on the brain that affect the brain's ability to regulate behavior.

Topographical Mapping

Core Idea

Major sensory and motor systems are topographically mapped. That is, the body, both inside and out, is mapped by the nervous system. Major sensory systems map the external world within their own circuitry. Likewise, the nervous system contains a mapped control over the muscles of the body. Mapped regions may have different inputs or outputs or may share the same ones. Maps are interconnected so that projections from one map to another trigger a back projection to the first map.

Mapping can persist at all levels in a given pathway.

Terms

basal ganglia — several clusters of neurons beneath the cerebral cortex that collectively modulate and help to coordinate body movements, as well as having other, non-motor functions.

body (spinal) segment — the body can be mapped according to the neuronal pathways to and from specific zones of the spinal cord. For example, both sensory and motor pathways of certain muscles reside in specific regions of the spinal cord.

hippocampus — a phylogenetically old kind of cortex, folded in under the neocortex, that is especially involved in emotional behavior and in memory formation.

hypothalamus — a small zone on the ventral surface of the brain. This area contains several distinct clusters of neurons that are important for regulating visceral and hormonal functions.

mapping — maps are neuronal representations (sometimes highly abstracted) of the real world. A map is a point-to-point representation of the real-world environment in which an animal lives.

thalamus — a group of many neuronal clusters along the midline of the brain, lying just in front of the brainstem and underneath the cerebral cortex. These clusters generally are topographically segregated for various sensations from specific parts of the body.

topographical — a spatial representation of information in the environment (can include internal environment of the body) is projected onto neuronal circuitry. The representation of the environment cannot be "graphed" in the usual sense of the word, but can be revealed and studied by various physiological measures such as electrical recordings from various regions within the mapped areas.

Explanation

The body, both inside and out, is mapped by the nervous system. Major sensory systems, such as vision and hearing, map the external world within their own circuitry. Locations in a three-dimensional sensory world are represented in the central nervous system neurons in such a way that neighboring locations in the sensory world also are represented in neighboring neurons in the nervous system. Likewise, in motor systems in the nervous system, neurons that activate certain muscles have neighboring neurons that activate neighboring muscles. These topographical maps constitute an inner model of the body. To explain this model in terms of neural function, we can think of a model as a:

an IMPLEMENTATION (nerve impulse patterns)
of a REPRESENTATION (topographical maps)
of an ABSTRACTION (sensory transduction/motor programs)
of a REALITY (physical stimuli/?)

Note that it is not so obvious what the "reality" basis is for motor programs. The underlying reality must include some kind of combination of muscle and bone anatomy, neural circuitry, and various degrees of intentionality.

We know that topographical maps exist because with appropriate monitoring techniques, such as microelectrodes that can record responses at various points along a sensory or motor pathway, an observer can witness the point-to-point projections of activity. Conversely, if one knows, from electrical recordings for example, the anatomical locus of a projection, the information flow along the pathway can be mimicked by electrical stimulation or be abolished by a lesion that is strategically placed in the topographical mapped area.

Not all parts of the brain have clear topographical mapping. Such non-mapped areas include the hippocampus, hypothalamus, and basal ganglia. How these non-mapped regions interact with the mapped systems remains among the great enigmas of neuroscience.

It is also important to address the issue of "hard wiring." Many of the known mapped pathways in brain are indeed created under genetic control during early development of the brain. These seem to be largely independent of any influence of learning, and this is certainly true for pathways in the spinal cord and brainstem. However, many studies have shown that depriving young, developing animals of a specific kind of stimulus can prevent them from developing the neural pathways in higher brain areas such as cerebral cortex for detecting such stimuli. The corollary is that sensory experience in early stages of development must be involve the selection of circuitry used to process those kinds of stimuli. Over time and repetition, these circuits can become permanently dedicated to that particular function.

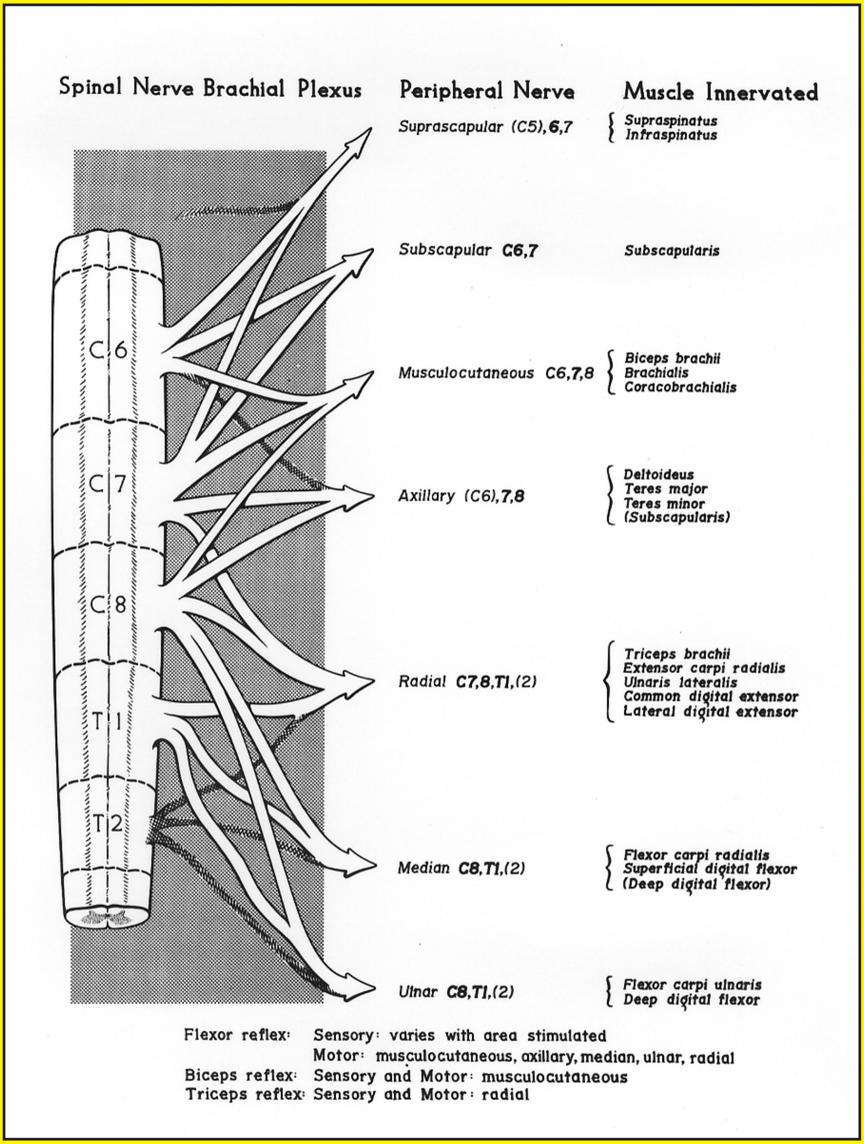
Examples

The simplest example of mapping is found within the spinal cord. A restricted portion of the body is mapped by a few specific neurons in the part of the spinal cord that is part of the same body segment. The projections from the cord into the brain retain a topographic segregation in the first relation station in the subcortical part of the brain known as the thalamus. The bodily mapped representations in the thalamus are maintained in the projections to the sensory cortex. As mentioned earlier, the sensory information is also routed in parallel in a non-mapped form via the central core of the brainstem. From there, projections go to diffuse areas of the cortex other than the sensory cortex.

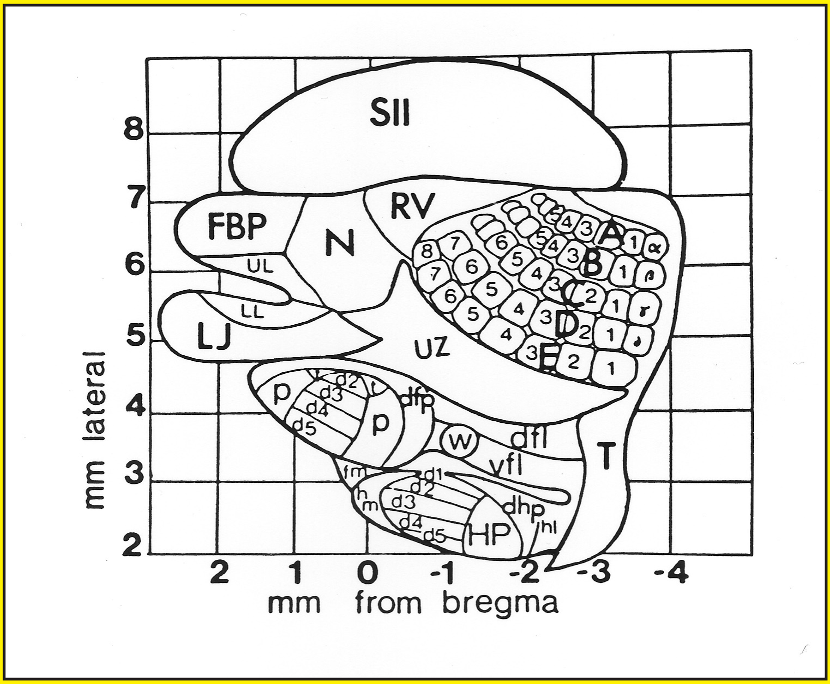
This has substantial clinical application. From knowing the topography of a sensory projection, for example, one can predict the clinical effects of a lesion at a particular point in the spinal cord. Conversely, from careful observation of clinical signs, particularly spinal reflexes, one can predict the locus of a lesion.

The projections from the cord into the brain retain a topographic segregation in the first relay station in the subcortical part of the brain known as the thalamus. The bodily mapped representations in the thalamus are maintained in the projections to the sensory cortex.

Topographic mapping is also a prominent part of the architecture of the higher parts of the nervous system, including much of the cerebral cortex. However, the clinical applications of this knowledge are not as straightforward as in the case of spinal pathways. In the cortex, there are regions where the body is mapped, both in terms of sensations and motor control. The precision of sensation or motor control is more or less proportional to the amount of map and number of neurons that participate in that function.



Segmental innervation from the regions of the spinal cord that give rise to the brachial plexus in dogs. Note that specific regions of the cord specifically innervate different muscle groups (from DeLahunta, A. 1983).



Topographically detailed representation of the various parts of the skin of anesthetized rats in the primary sensory cortex. Map was constructed by microelectrode recording from neurons in the sensory cortex, while stimultaneously stimulating different regions of skin. There is disproportionate representation of the vibrissae (A-E, 1-8) and the skin of the paws (dorsal hindpaws: dhp; dorsal forelimb: dfl; palm: P) and digits (d1-d5). Less well-represented areas include the trunk (T), nose (N), lips (UL, LL), lower jaw (LJ). Zone UZ was unresponsive in anesthetized rats. SII = secondary sensory cortex, which was unmapped. From Chapin and Lin (1984).

Taken at face value, the idea of mapping can be very misleading. Take, for example, the observation from magnetic imaging studies on monkeys that indicate the presence of three patches of neocortex in the left hemisphere that a monkey uses to discriminate among pictures of faces of other monkeys. Electrical recording from individual neurons in these cortical patches revealed a high degree of face-response selectivity, with neurons in these areas being some 50 times less responsive to non-face stimuli. MRIs of humans indicated a small face-selective area in the bottom posterior region of the right hemisphere, while other small areas were selective for seeing bodies or scenes or visually presented words. These findings tempt us to conclude that the cortex is broken down into modules, with one patch dealing with faces, another with bodies, and so on. Yet, we must realize that the imaging technology available only allows us to see the "sweet spots" of such processing. Each of these cortical areas is connected to many widespread regions in both hemispheres and these are no doubt engaged in the processing associated with the respective sweet spots, but have not been detected because of limited sensitivity and resolution of current imaging technology.

A more compelling example of how we can overestimate topographical mapping comes from what we have learned about the two well-known "speech centers" in the left cerebral cortex. Each is about the size of a half dollar coin, with one center controlling the tongue and lip movements needed for speech and the other controlling semantic interpretation of language. Destruction of these centers, as sometimes occurs for example with stroke, can render a person incapable of speech. Magnetic resonance imaging of bilungual people even indicates that the areas are engaged irrespective of which language a bilingual speaker chooses to use. It does not, however, necessarily follow that speech capability is confined to these small areas. Indeed, it seems highly unlikely that all the memory store associated with language can be held in just these small areas of cortex, especially in people who speak many languages. Brain imaging studies in bilinguals show that neurons in the left caudate nucleus, one of the basal ganglia located deep within the forebrain, is activated during language processing and is sensitive to which particular language a bilingual chooses to use at any given moment. Study of people with damage in the left caudate nucleus revealed that even a trilingual patient retained comprehension in all of her languages. However, her spontaneous use of the languages was corrupted, characterized by inability to control which language was used, with spontaneous and uncontrollable choice of language.

Thus, it would appear that the caudate normally helps to monitor and control the use of neuronal populations in the language center. It is still not clear where all the information associated with language, such as grammar and vocabulary, is stored. Most likely, language is a process widely distributed throughout many areas of the brain. In such a case, the language centers should be thought of as perhaps crucial nodal points in multiple distributed circuits.

Related Ideas

Ensembles of Dynamic Neural Networks (Learning & Memory)
Modularity
Parallel, Multi-level Processing (Information Processing)
Emergent Properties (Information Processing)
Sensory Modalities & Channels (Senses)
Plasticity (Development)

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