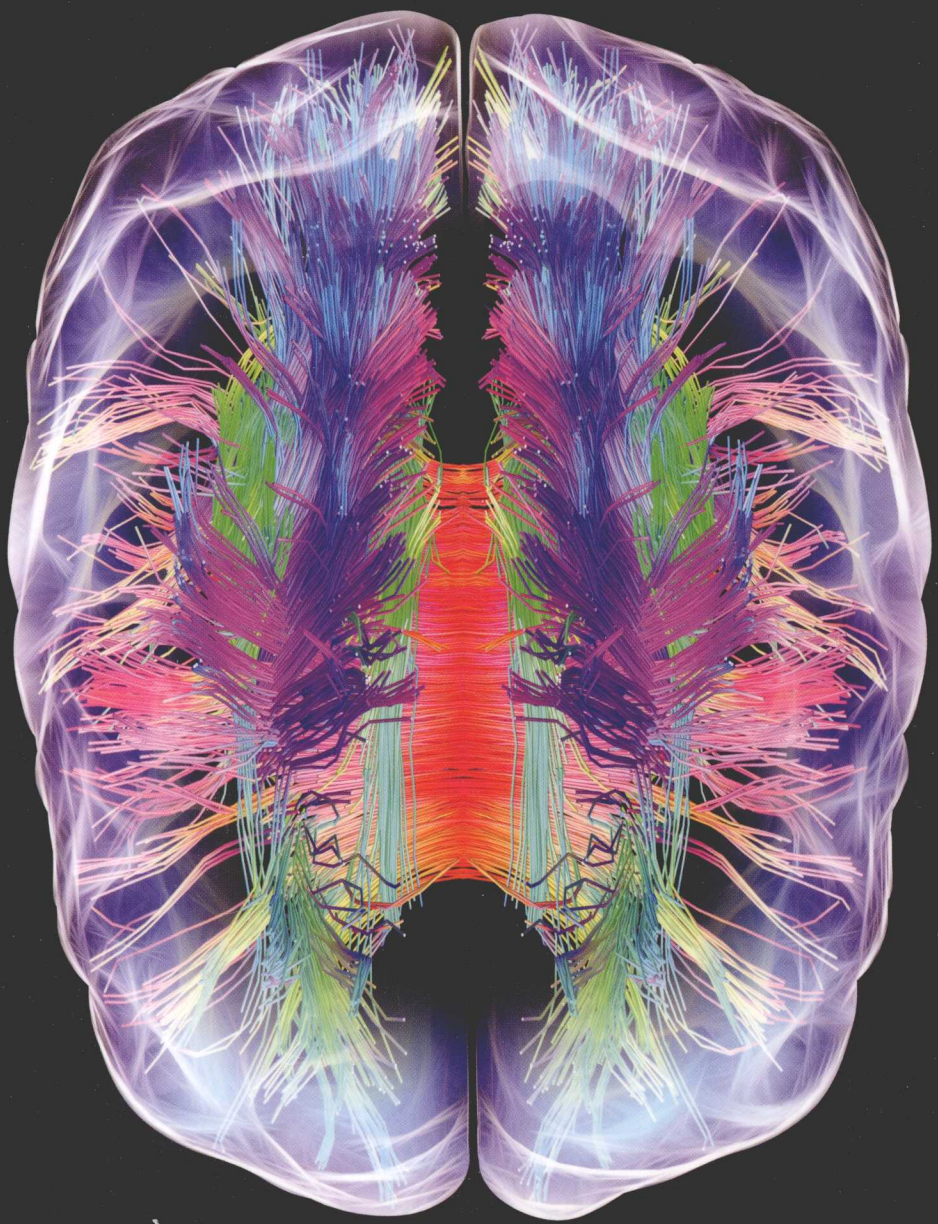
ESSENTIALS

ESSENTIAL CLINICAL NEUROANATOMY

THOMAS H. CHAMPNEY



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Essential Clinical Neuroanatomy

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Preface

Essential Clinical Neuroanatomy is the first neuroanatomy text that consistently illustrates and discusses the anatomy of the central nervous system from the clinical perspective. All of the illustrations are provided in the clinical view (using the axial radiologic standard of computed tomography and magnetic resonance imaging). This provides consistency throughout the text and throughout the career of the reader. In addition, the neural pathways are color coded for easier recognition and recall with green indicating sensory components, red indicating voluntary motor components, and purple indicating involuntary (autonomic) components. The clinically relevant neuroanatomy is highlighted, with case studies, clinically-oriented study questions, and clinical boxes of interest. Anatomic details that do not have direct clinical relevance are de-emphasized.

The text is divided into two main sections: the first eleven chapters provide the neuroanatomy of the central nervous system, while the last seven chapters provide descriptions of the sensory, motor, and integration systems within the central nervous system. Each chapter begins with objectives and an outline of the material to be covered. Within each chapter, highlighted clinical boxes are presented, while case studies and clinically relevant multiple choice questions are found at the end of each chapter. Each chapter contains a list of additional readings that include more detail-oriented textbooks, as well as current review articles.

This text is designed for those in the health sciences who require a basic introduction to clinical neuroanatomy. This can include allied health students, first-year medical students, dental students, and neuroscience students. Because of its essential nature, it can be useful for those reviewing neuroanatomy for major licensing or competency examinations.

Thomas H. Champney

Acknowledgments

The development and production of *Essential Clinical Neuroanatomy* utilized the skills and strengths of numerous individuals. First, Dr Ron Clark, my predecessor at the University of Miami, generously provided access to his photographic files, his illustrations, and his notes. The foundation of the book is built on his many years of teaching neuroanatomy. Second, all of the clinical imaging (radiographs, computed tomographs, magnetic resonance images) were graciously provided by Dr Charif Sidani, a neuroradiologist associated with the University of Miami. He provided many hours of help in recommending and selecting images for use in the text.

The editorial staff at Wiley Blackwell were extremely helpful in all phases of this project. Specifically, Elizabeth Johnston, Karen Moore, and Nick Morgan were professional and highly organized. In addition, the excellent illustrations by Jane Fallows and Roger Hulley are an integral part of this project. Any anatomy text is only as good as its illustrations. All of these individuals made the daunting task of this project much more manageable.

Finally, I express my gratitude to all of the students who have provided feedback on the neuroanatomy lectures that are at the center of this text. Their comments and critiques on the lecture material provided the focus for teaching the essentials of clinical neuroanatomy.

Thomas H. Champney

About the companion website

Don't forget to visit the companion website for this book:

www.wileyessential.com/neuroanatomy

There you will find valuable material designed to enhance your learning, including:

- More multiple-choice questions for self-testing
- Interactive flashcards with on/off label functionality
- PowerPoint figures from the book for downloading

Scan this QR code to visit the companion website:

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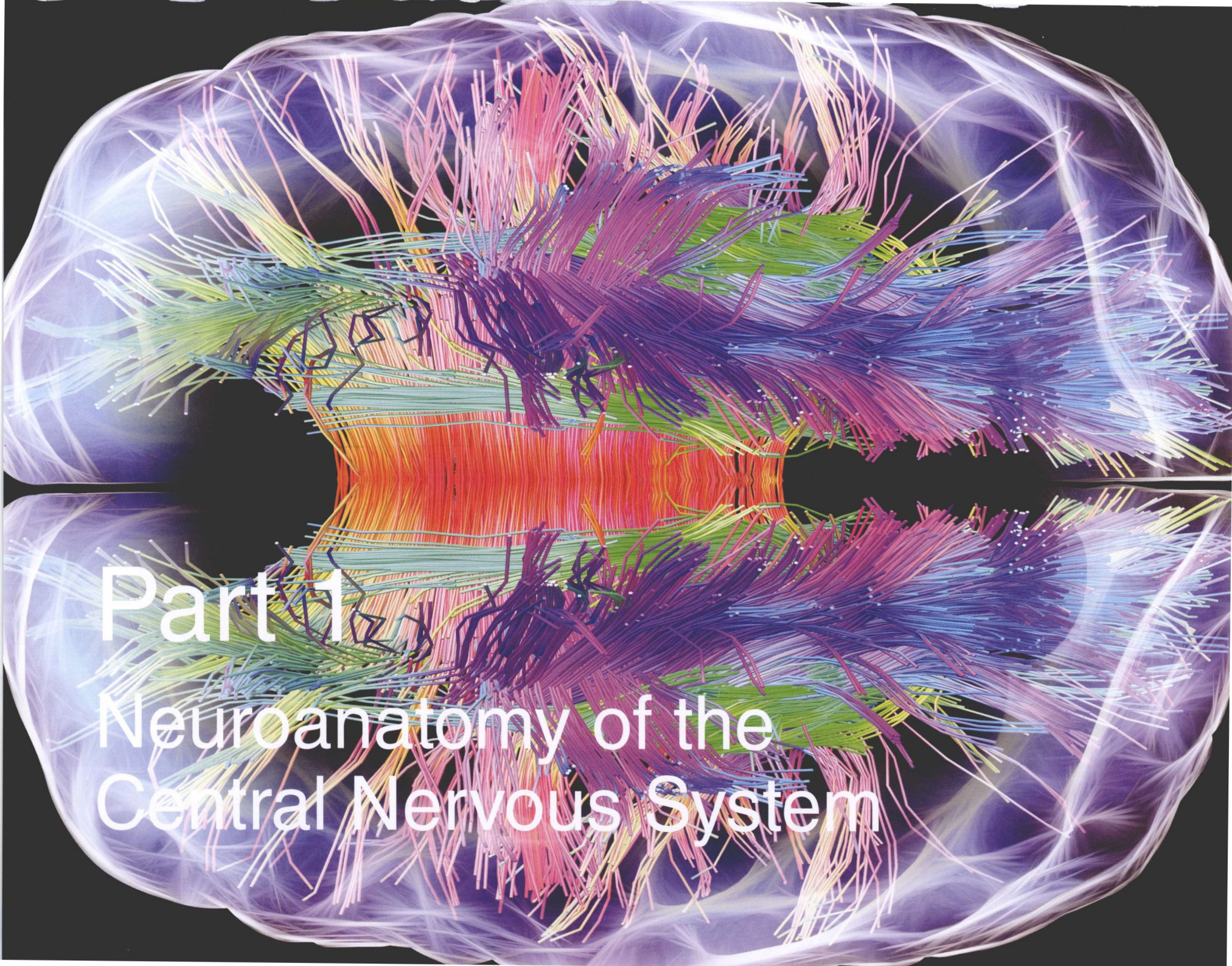

Part 1
Neuroanatomy of the Central Nervous System

CHAPTER 1

Overview of the nervous system

Learning objectives

1. Describe the basic subdivisions of the human nervous system.
2. Understand basic neuroanatomical terminology.
3. Identify the major structures on the external surface of the gross brain.
4. Identify the major structures on the midsagittal surface of the brain.
5. Identify the cranial nerves.

Divisions of the nervous system 5

Anatomic

1. Central nervous system (CNS)
   a) Brain and spinal cord
   b) Collection of nerve cell bodies = nucleus
2. Peripheral nervous system (PNS)
   a) Peripheral nerves
   b) Collection of nerve cell bodies = ganglia

Functional

1. Sensory (afferent)
   a) General – touch
   b) Special senses – sight, sound, taste, smell, balance
2. Motor (efferent)
   a) Voluntary (somatic) – skeletal muscle
   b) Involuntary (autonomic) – smooth and cardiac muscle
      i. Parasympathetic – craniosacral (III, VII, IX, X, S2–S4)
      ii. Sympathetic – thoracolumbar (T1–L2)
3. Integrative – interneurons within the CNS

Components of the nervous system 8

Neurons

1. Highly specialized, excitable cells
2. Morphologic diversity

Glia – supporting cells

1. Schwann cells (neurolemmocytes) – myelin producing
2. Oligodendrocytes – myelin producing

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3. Astrocytes – nutritional support
4. Microglia – macrophages (immune support)

Neurons

Cellular structure

1. Dendrites
2. Axon
   a) Axon hillock
   b) Terminal arborization/terminal boutons
   c) Synapse/synaptic vesicles
   d) Anterograde/retrograde flow
3. Soma (perikaryon, cell body)
   a) Nucleus/nucleolus
   b) Nissl bodies (rough endoplasmic reticulum and polyribosomes)
   c) Lipofuscin
4. Cell membrane (plasmalemma, neurolemma)
5. Types: unipolar, bipolar, multipolar, pseudounipolar

Glia – central nervous system

Oligodendrocytes – myelin production; one oligodendrocyte for many axons

Astrocytes – support cells, glial fibrillary acid protein (GFAP), end feet

1. Fibrous astrocytes – white matter
2. Protoplasmic astrocytes – gray matter

Microglia – macrophage-like, scavenging cells

Ependymal cells – columnar, ciliated cells lining the ventricles

Central nervous system

Gray matter

1. Nerve cell bodies (nuclei)
2. Dendrites and axons
3. Glia

White matter

1. Nerve fibers (axons) – myelinated
2. Glia

Brain neuroanatomy

Orientation of the brain – 90 degree rotation at midbrain flexure

1. Superior – inferior
2. Anterior – posterior
3. Dorsal – ventral
4. Rostral – caudal

Planes of the brain

1. Sagittal plane
   a) Midsagittal
   b) Parasagittal
2. Horizontal plane (transverse, axial)
3. Frontal plane (coronal)

Views of the brain

1. Superior
   a) Interhemispheric fissure (sagittal)
   b) Precentral gyrus (primary motor)
   c) Central sulcus
   d) Postcentral gyrus (primary somatosensory)
2. Inferior
   a) Interhemispheric fissure (sagittal)
   b) Lateral fissure (Sylvian)
   c) Midbrain – cerebral peduncles
   d) Pons
   e) Medulla oblongata – pyramids, inferior olives
   f) Cerebellum
   g) Olfactory bulb and tract
   h) Optic chiasm and tract
   i) Infundibulum (pituitary stalk)
   j) Mammillary bodies
   k) Cranial nerves (12)
      i. Olfactory nerve (I)
      ii. Optic nerve (II)
      iii. Occulomotor nerve (III)
      iv. Trochlear nerve (IV)
      v. Trigeminal nerve (V)
      vi. Abducens nerve (VI)
      vii. Facial nerve (VII)
      viii. Vestibulocochlear nerve (VIII)
      ix. Glossopharyngeal nerve (IX)
      x. Vagus nerve (X)
      xi. Spinal accessory nerve (XI)
      xii. Hypoglossal nerve (XII)
3. Lateral
   a) Lateral fissure (Sylvian)
   b) Brain stem (midbrain, pons, and medulla)
   c) Cerebellum
   d) Central sulcus
   e) Precentral gyrus (primary motor)
   f) Postcentral gyrus (primary sensory)
   g) Lobes of the brain
      i. Frontal lobe
      ii. Parietal lobe
      iii. Occipital lobe (vision)
      iv. Temporal lobe (auditory)
   h) Insular cortex
   i) Superior temporal gyrus (auditory)
4. Midsagittal
   a) Frontal cortex
   b) Parietal cortex

Introduction

The nervous system is a remarkable communication system that can send a message from one part of the body to the brain, react to that message, and produce a response within seconds. The goal of this chapter is to introduce the components and organization of the nervous system. This may be a review for some, but it will set a foundation on which the remainder of the text can be built.

Nervous system organization

The nervous system can be described in two ways: anatomically or functionally. Anatomically, the nervous system is divided into a central component (**brain** and **spinal cord**) and a peripheral component (**cranial nerves** and **peripheral nerves**). The central component, called the **central nervous system (CNS)**, is made of groups of neuronal cell bodies (called **nuclei**), their dendritic and axonal processes, as well as many

supporting cells (**glia**). The peripheral component, called the **peripheral nervous system (PNS)**, is composed primarily of axonal neural processes, but there are also small collections of neuronal cell bodies (called **ganglia**) and only one type of supporting cell (**Schwann cells** or neurolemmacytes) (Figure 1.1). It should be borne in mind that a collection of neural cell bodies has a different name depending on its anatomical location: ganglia in the PNS and nuclei in the CNS. These nuclei are collections of cell bodies and should not be confused with cellular nuclei that contain chromosomes. Also, to complicate matters, there are some nuclei in the central nervous system that are referred to as the basal ganglia. This is not the best nomenclature and can be confusing.

Functionally, the nervous system is divided into three components: a **sensory** (**afferent**, input) component; an **integrative**, decision-making component; and a **motor** (**efferent**, output) component (Figure 1.1). The sensory portion contains peripheral receptors that respond to numerous factors (e.g. touch, vibration, pain, chemical compounds (taste, smell), light (vision), sound (hearing), and position sense (balance)). These receptors interact with peripheral axons that propagate the signal towards the central nervous system. The majority of these neurons have their cell bodies in the periphery (in ganglia) and send a process into the central nervous system carrying the signal. Within the central nervous system, these processes can take a number of paths. They can ascend to inform the brain (cortex and cerebellum) of the information and they can also synapse in the spinal cord to produce reflexes. This information can be relayed by other neurons to numerous portions of the central nervous system, where the information can be **integrated** with other inputs and a **motor output** can be executed. As a simple example, you could place your hand on a hot stove and feel the heat and pain associated with the stove. You would then rapidly remove your hand by a reflex arc with the muscles in the hand, forearm, and arm. This will actually occur within the spinal cord and before you have any conscious awareness of the pain. If you want to continue to "cook" your hand, you can voluntarily override the reflex arc and force

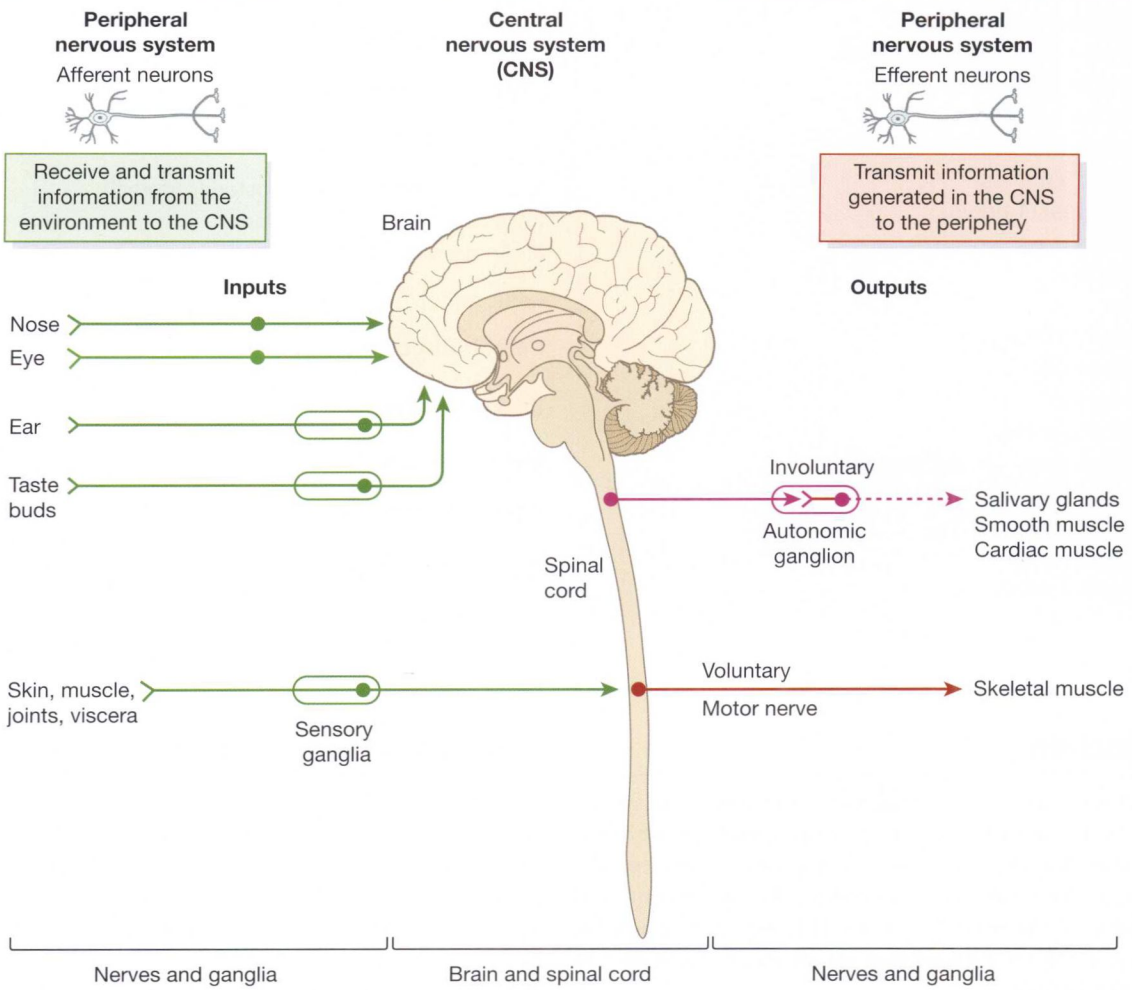


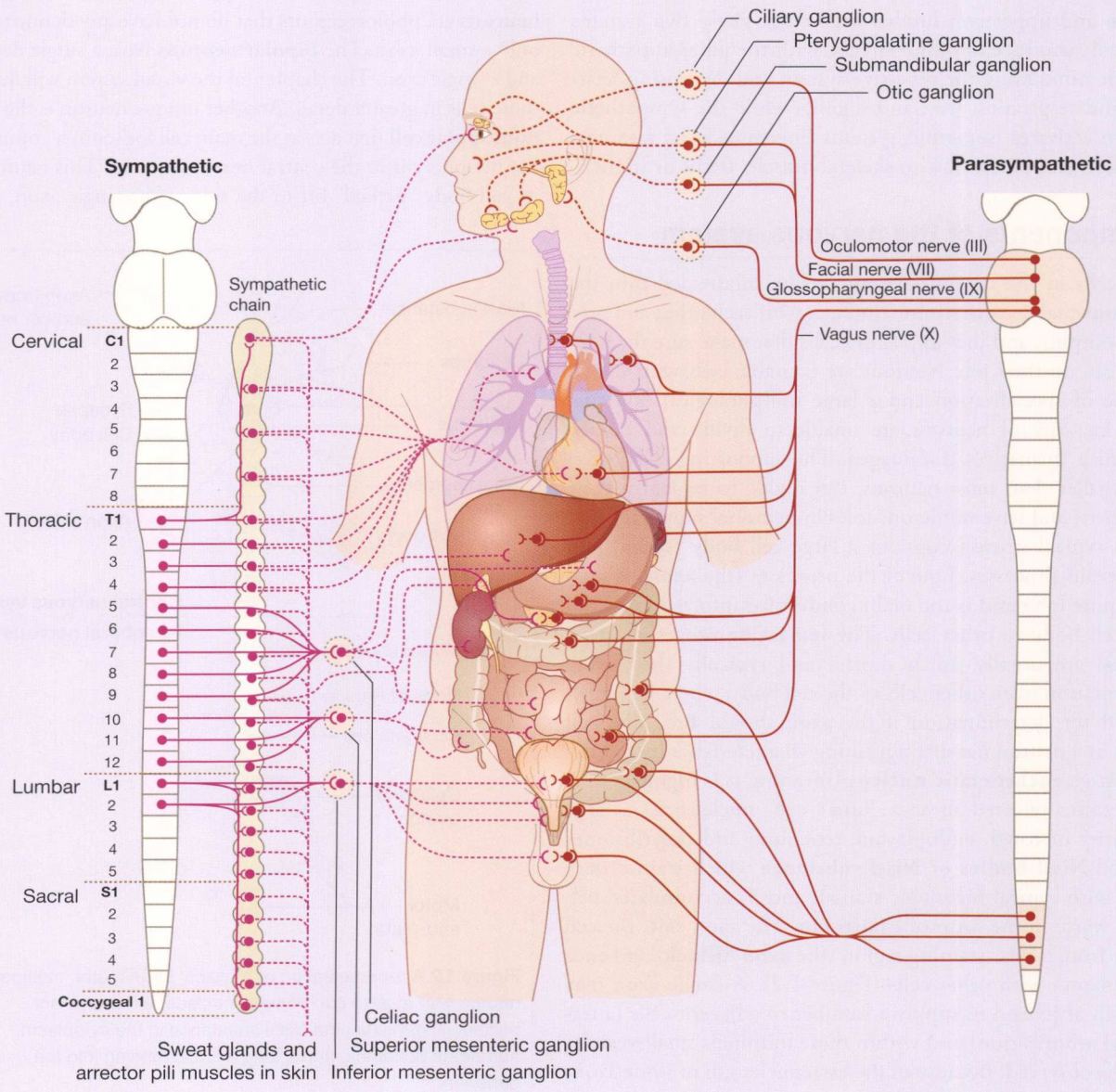
Figure 1.1 A diagrammatic representation of the central and peripheral nervous system with a collection of central cell bodies referred to as a nucleus (plural: nuclei), while a collection of peripheral cell bodies is referred to as a ganglion (plural: ganglia).

Clinical box 1.1

The autonomic nervous system is particularly important in clinical medicine since dysfunction of the heart, lungs, and digestive systems can be linked to autonomic nerves. Physicians modify a patient's autonomic nerve function by prescribing drugs that stimulate or inhibit the firing of these nerves or their receptors. For example, individuals with heart problems can be prescribed "beta blockers" which are drugs that interact at the beta adrenergic receptors in the heart modifying the autonomic tone to the heart. It is, therefore, quite important to know the organization and distribution of the autonomic nervous system.

Both of the subdivisions of the autonomic nervous system (the parasympathetic and sympathetic systems) are a two neuron chain in which acetylcholine is released at the preganglionic synapse. In the parasympathetic nervous system, acetylcholine is also released at the postganglionic synapse with the target organ, while in the sympathetic system, norepinephrine is released at the postganglionic synapse (except for sweat glands which also use acetylcholine). Therefore, cholinergic compounds can interact at both systems, while noradrenergic compounds only affect sympathetic function.

For further details on this system, consult a basic anatomy textbook (Moore, *et al.*, 2014), as well as a neuropharmacology textbook (Stahl, 2013).



your hand to stay on the stove. This is using the integrative function of the brain to direct a willful activity.

With the previous discussion, the output used skeletal muscles to move an extremity. This is called a **voluntary** (**somatic**) motor response. There is also an **involuntary** (**autonomic** or visceral) motor response that drives smooth muscle and cardiac muscle. For example, you can see a portion of your favorite food, hot and ready for you to eat, and you will begin to salivate and your stomach may make sounds. These are involuntary smooth muscle actions as you prepare to eat. The **autonomic motor system** is further subdivided into two components: a **parasympathetic** and a **sympathetic** portion. The parasympathetic portion has its central neuronal cell bodies located in the brain stem or in a small portion of the sacral spinal cord (the second through fourth sacral nerves). The sympathetic system has its central neuronal cell bodies located in the spinal cord in the thoracic region and upper two lumbar segments. These two systems generally produce opposite effects, with the parasympathetic system stimulating the digestive system and decreasing heart rate and respiration (rest and digest), while the sympathetic system activates numerous systems (increases heart rate, respiration, and blood flow to skeletal muscle: flight or fright).

Components of the nervous system

The cells in the nervous system can be subdivided into the **neurons** that react to stimuli, interact with each other and produce outputs, and the supporting cells that make sure the neurons can do their job. Neurons are excitable cells with a high degree of specialization and a large morphological diversity. The majority of neurons are unable to divide and cannot replenish themselves if damaged. The supporting cells (**glia**) are smaller than most neurons, can divide to replenish their numbers, and have numerous roles in neuronal support.

A typical neuron contains a large cell body (**soma**) and numerous processes. One of the processes (the **axon**) is usually quite long and is the main conduit for information from the cell body to other cells. The remaining processes (**dendrites**) are usually much shorter and typically they bring information from other cells to the cell body, where it is summated for determination if the axon should fire. The cell body of a neuron has distinguishing characteristics including: 1) a large **euchromatic nucleus** (meaning it is highly active) sometimes referred to as a "bird's eye" nucleus; 2) a large quantity of rough endoplasmic reticulum and polyribsomes (called **Nissl bodies** or **Nissl substance** which stain a dark blue with typical histologic stains); and 3) accumulated cellular waste in the form of **lipofuscin**. The axon exits the cell body from a clear staining region (the **axon hillock**) and ends at synapses with other cells (Figure 1.2). A single axon may branch at its end to supply a number of adjacent cells (a terminal arborization) and within these terminals small **vesicles** can be observed. Because of the extreme length of some axons (from the spinal cord to the foot – over a meter in length), there are mechanisms which allow for transport of materials to and from one end of the axon to the other. Flow from the cell body to the terminals is termed **anterograde axoplasmic transport**, while flow from the terminal to the cell body is termed **retrograde axoplasmic transport**. As mentioned previously, the neuron is an excitable cell and this excitation is maintained and modified by the specific characteristics of the neuronal cell membrane (the plasmalemma or neurolemma). The membrane has numerous ion channels and ion pumps that can maintain an ionic gradient across the membrane, producing the excitability.

A typical neuron is described as a large cell body and nucleus with numerous small dendrites and one very long axon. This is a **multipolar neuron**, which is found in many parts of the nervous system (Figure 1.2). There are, however, a number of other morphologically distinct neurons. For example, in the retina, there are both unipolar and bipolar neurons. The **unipolar neurons** are photoreceptors that do not have any dendrites and only a small axon. The **bipolar neurons** have a single dendrite and a single axon. The chapter on the visual system will describe these cells in greater detail. Another unique neuron is the **pseudounipolar cell** that acts as the main cell for sensory input from the periphery into the central nervous system. This neuron has its cell body "parked" off to the side of the single axon, which

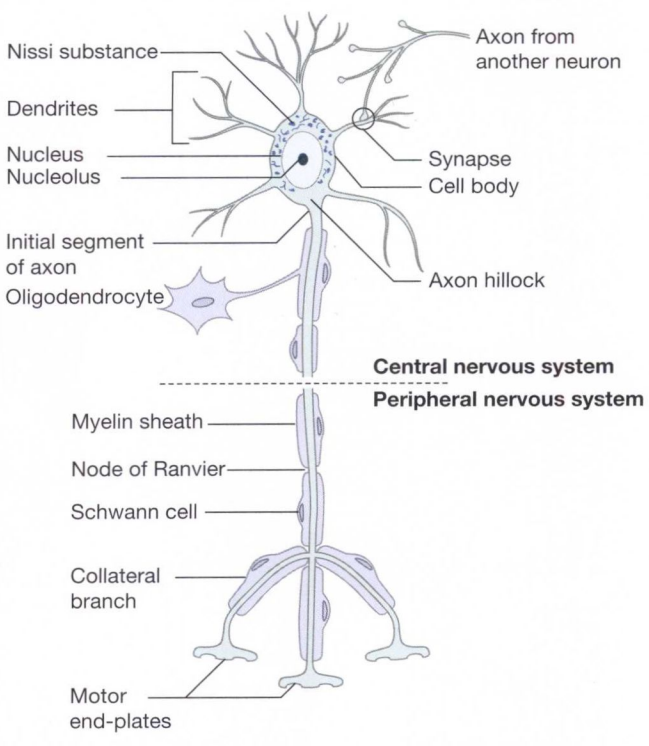


Figure 1.2 A representation of a typical large motor, multipolar neuron with a large euchromatic nucleus and prominent nucleolus, dark staining Nissl substance in the cytoplasm, numerous dendrites, and a long axon extending into the periphery.

has a peripheral projection and a central projection. This allows for rapid input of sensory information from the periphery to the central nervous system without the need to summate or interpret the information at the cell body.

The glial supporting cells are found in both the peripheral and central nervous systems. In the peripheral nervous system, the **Schwann cell** (neurolemmacyte) protects the axons as they are distributed throughout the body. In some cases the Schwann cells simply enclose the axons in their cell membrane, providing nutritional and mechanical support. These are termed **unmyelinated axons** and there may be many of this type of axon supported by one Schwann cell. In other cases, a single Schwann cell will support only one portion of an axon and it will wrap its cell membrane around the axon numerous times, insulating the axon. This is termed a **myelinated axon**. Since one Schwann cell only myelinates a small portion of an axon, other Schwann cells are required to myelinate the remaining length of the axon. Where the myelin layers of the adjacent Schwann cells meet, there is a small gap between the cells, a **node of Ranvier**. While this myelin sheath insulates and protects the axon, it also modifies the ionic flow across the axon cell membrane, producing a stronger, faster, and more reliable axonal signal (saltatory conduction). Therefore, myelinated nerves are faster than their unmyelinated counterparts.

In the central nervous system, there are other glial cells that provide support. The myelin producing cells in the central nervous system are the **oligodendrocytes**. They produce myelin sheaths for a number of axons in the area. The ability to myelinate neurons has important clinical aspects, since there are diseases, such as multiple sclerosis, that can affect myelination and neural function. Another glial cell within the central nervous system is the **astrocyte**. The astrocyte is a supporting cell that provides nutrition for neurons, modifies neurotransmitter uptake, and, importantly, has foot processes that surround the blood vessels in the brain, producing a special immunologically privileged area: the **blood-brain barrier**. There are two types of astrocytes; the fibrous astrocyte associated with white matter and the protoplasmic astrocyte associated with gray matter. Astrocytes can be immunohistochemically identified by the presence of a particular intermediate filament: **glial fibrillary acidic protein (GFAP)**. This protein can also be used in clinical diagnosis of central nervous system tumors. If GFAP is present in a tumor, it means that the tumor was originally derived from astrocytes. Another glial cell within the central nervous system is the **microglia**. These are small macrophage-like cells that act as a local immune response agent, phagocytosing foreign materials. The microglia can be identified using similar immunologic techniques that would identify macrophages in the periphery. An additional supporting cell within the central nervous system is the **ependymal cell**. This is an epithelial, simple columnar, ciliated cell that lines the ventricular system. Modified versions of these cells are responsible for the production of cerebrospinal fluid.

Clinical box 1.2

There are numerous diseases associated with improper glial cell function. **Multiple sclerosis** is an autoimmune disease in which a patient develops antibodies to their own myelin sheaths. The antibodies damage the myelin sheath covering the axon and disrupt the neuronal firing. There are different types of multiple sclerosis, depending on the severity and progression of the disease. There is also an interesting global distribution of the disease, with more cases found in countries further away from the equator and more cases in industrialized nations. The reason for this distribution is not known.

Central nervous system structure

When examining the central nervous system, it is apparent that there are two distinct regions. Historically, these regions were named by their color. One region looked white and was called the **white matter**. This is due to the highly myelinated nerve fibers present in this region. Myelin is made of numerous wrappings of cell membrane and therefore contains large quantities of cholesterol, phospholipids, and other lipid-based compounds. This produces the white appearance of the white matter. The other region of the central nervous system contains both myelinated fibers and neuronal cell bodies. This area is, therefore, less white and is referred to as **gray matter**. Therefore, the gray matter contains neuronal cell bodies, axons, and glia, while the white matter contains only axons and their supporting glial cells (Figure 1.3).

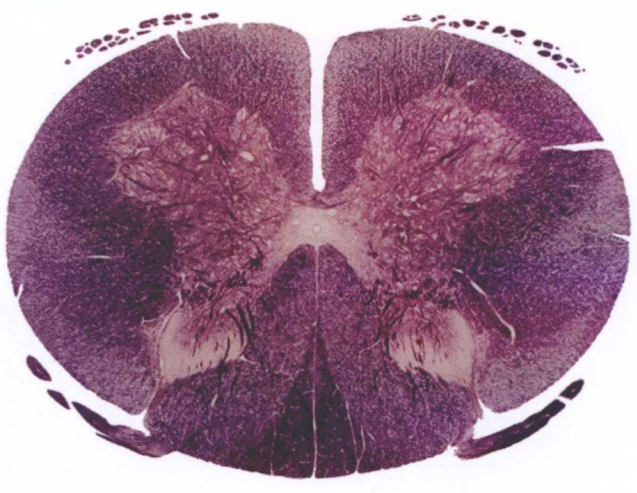
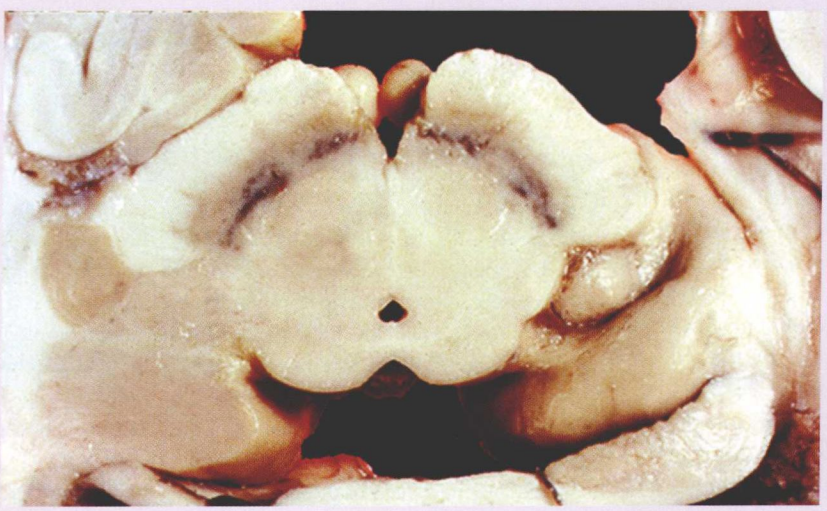


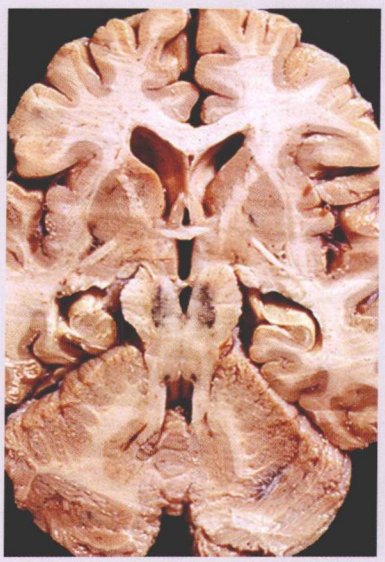
Figure 1.3 A typical cross section of the spinal cord, stained to indicate the presence of myelin, with the outer white matter (containing axons and glia) more densely stained and the inner gray matter (containing neuronal cell bodies, axons, and glia) less densely stained. Note the clinical orientation, with the posterior aspect of the spinal cord at the bottom of the image.

Clinical box 1.3

There are numerous methods utilized to view the components of the central nervous system. Clinically, the use of plain films, computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound are used routinely to visualize a patient's brain or spinal cord. Chapter 18 on Imaging Essentials provides details on these and other techniques that are used clinically. However, the resolution of these techniques is presently not detailed enough to provide good differentiation of the nuclei and tracts within the central nervous system, so neuroanatomists still rely on specific histologic methods to visualize the components of the nervous system.

The simplest visualization of the nervous system is with the naked eye. Fresh tissue sections of the brain and spinal cord can be viewed with white matter and gray matter easily distinguishable. Structures such as the substantia nigra in the midbrain are easily observed in fresh tissue.





These are fresh tissue sections of the midbrain and surrounding cortical tissues without any staining or treatment. Note the two dark regions in the upper middle portion of the field (the substantia nigra). These areas are normally dark due to the presence of neuromelanin in the cells. The white matter and gray matter can also be observed, although the gray matter actually has a brown coloration in fresh tissue.

Similar sections of midbrain and cortex can be histologically processed to indicate the presence of myelin (a myelin stain). This is a typical presentation that highlights the tracts and nuclei of the central nervous system.