# NEUROSCIENCE FUNDAMENTALS

*for*

## Communication Sciences and Disorders

**THIRD EDITION**

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# PREFACE

The Third Edition of ***Neuroscience Fundamentals for Communication Sciences and Disorders*** marks the most comprehensive and thoughtful revision of the book to date. This edition is a direct response to the evolving needs of students and instructors. Building on the strengths of earlier versions, the Third Edition provides a more intuitive, clinically impactful, and pedagogically efficient learning experience. It adds valuable new tools to enhance both instruction and student application.

*Neuroscience Fundamentals for Communication Sciences and Disorders* (*NFCSD*) was originally developed with three primary audiences in mind. First, it is designed for senior undergraduate and graduate students in communication sciences and disorders, providing a comprehensive, richly illustrated, and accessible introduction to the neuroanatomy and neurophysiology of the human nervous system. Written in a brain-and-behavior style, the text emphasizes an integrative understanding of brain–behavior relationships that are central to evidence-based practice in speech, language, and hearing rehabilitation.

Second, the book serves as a practical reference for clinicians. It is intended as a readable and usable resource that clinicians can return to without the need for additional formal coursework. The accessible writing style, extensive illustrations, and explanatory analogies are designed to support clinical decision-making, refresh foundational knowledge, and facilitate client and caregiver education about the brain-based nature of communication disorders.

Finally, *NFCSD* was written as a teaching resource for faculty responsible for neural bases coursework, including those without specialized neuroscience training. The text is designed to function as a faculty guide for course development and lecture planning, with flexible content, adaptable analogies, and companion lecture materials that instructors are encouraged to customize to meet their needs.

## New Third Edition User Features That Enhance Learning and Clinical Application

To enhance student comprehension and the development of clinical reasoning skills, the Third Edition introduces new and updated features:

- **Addition of 45 clinical case studies creates a new dimension to the Third Edition.** The new case studies are substantially detailed and strategically integrated throughout the chapters to connect neuroanatomical structure and functional discussions with real-world communication-related disorders.
- **Over 80 summary tables**, including nearly 40 new tables in this edition, are now available to condense key information from the text and support quick review and study by students.
- **Refined and updated figures** to better support visual learning and integration with the text.
- **Expanded PluralPlus student resources**, designed to reinforce understanding and support diverse learning styles. Student resources include:
  - Chapter study guides
  - Study worksheets with answers
  - A cranial nerve testing guide with a table listing typical negative findings of cranial nerve evaluations and their clinical implications
  - Unlabeled figures to practice naming
  - Supplemental handouts that simplify selected complex concepts into more accessible language
- **Updated PluralPlus instructor resources** for faculty using the book to fit different semester schedules and timing, and provide greater flexibility in how instructors choose to deliver and organize their materials. Instructor materials include:
  - Inclusion of updated exams (with answers)
  - Updated PowerPoint lecture slides
  - Labeled and unlabeled figures for inclusion in lecture slides or self-prepared exams
  - **NEW FEATURE:** Addition of different syllabi versions designed to fit various semester lengths and student preparation levels. Student reading schedules are also included to assist faculty in flexibly customizing the book for their needs and students' backgrounds.

## Revised and More Intuitive Content Structure to the Third Edition

Complementing the textbook's new and updated user features, the content for the Third Edition has undergone substantial reorganization from the Second Edition into four new thematic sections. The content within each section has been better aligned, refined, and organized to enhance the progression of neuroscience topics underlying healthy and disordered communication. The new thematic sections are:

- **Section 1:** Foundations: Neuron Structure and Signaling
- **Section 2:** Neuroanatomy: Peripheral and Central Nervous Systems
- **Section 3:** Sensory Systems: Somatosensation, Audition, Vision, and the Chemical Senses
- **Section 4:** Motor Systems and Sensorimotor Regulation

The Third Edition's significantly revised structure offers several key benefits, creating a more seamless flow of content that better highlights and clarifies the interconnections between neural systems. Examples of key content revisions include:

- **Revised and Streamlined Neural Structure and Signaling Chapters**
    - Early chapters on neuron structure and signaling have been revised and simplified for greater clarity by incorporating new analogies and clearer language to better support the student's conceptual learning of these often more abstract topics.
- **Neuroanatomy Chapters Reorganized to Enhance Progressive Learning**
    - The neuroanatomy chapters have been significantly revised by breaking lengthier chapters from the Second Edition into shorter, more focused, and digestible divisions. Through this approach, the neuroanatomy section has been expanded and reorganized into six progressively sequenced chapters that guide students from basic anatomical knowledge to the complex integrative systems that underlie communication, cognition, and behavior.
- **Speech, Language, and Hearing Integration**
    - A major revision to the Third Edition is the redistribution of speech, language, and hearing content closer to the neuroanatomical and functional discussions underlying each behavior. In contrast to the stand-alone chapters of the Second Edition, these topics are now woven directly into the broader neuroanatomical and systems-level narrative, helping students develop a more immediate understanding of communication and its neural underpinnings. A new dedicated chapter on the neural mechanisms of speech and language presents a streamlined discussion of selected theoretical models and significantly expands clinical coverage of neurologically based communication disorders.
- **Sensory System Section Enhancements**
    - The content on the auditory system is now presented in a clearer, logically ordered sequence, from peripheral hearing components to central auditory processing, providing a more cohesive learning experience. Content on the visual and chemical sensory systems has been revised and simplified to highlight key concepts and enhance understanding of these systems.
- **Content Integration for Motor Systems Section**
    - The stand-alone chapter on muscle tissue from the Second Edition has been considerably shortened and merged with content on the primary motor system. This new chapter offers a unified and streamlined overview that highlights the connection between the key elements of muscle contraction and direct motor control. A second new chapter is now dedicated solely to explaining indirect motor systems, providing clearer insights into their unique roles in motor skill and coordination.
    - Finally, all material related to neuroplasticity and sensorimotor learning, previously spread throughout the book in the Second Edition, has been consolidated into a final capstone chapter that emphasizes the brain's dynamic ability to adapt, learn, and recover from injury.

With these changes, the Third Edition of *Neuroscience Fundamentals for Communication Sciences and Disorders* aims to better prepare students to think like clinicians by helping them more easily identify patterns, connect systems, and understand how neuroanatomy and neurophysiological processes influence human communication. Whether revisiting the text or exploring it for the first time, this new edition seeks to give the user a clearer, more integrated, and cohesive understanding of the neuroscience of communication sciences and disorders.

As always, I believe that textbooks should be dynamic and evolving entities that grow and change as we learn more about our subject. Therefore, the content of this book is as current as possible, with every effort made to verify its accuracy against multiple independent sources. Despite these efforts, errors may still be present in the book, and for these I apologize in advance; the responsibility for any mistakes is mine alone.

# ABOUT THE AUTHOR

**Richard D. Andreatta, PhD**, is an ASHA Fellow and Professor in the Department of Communication Sciences & Disorders (CSD) and the Rehabilitation & Health Sciences Doctoral Program in the College of Health Sciences at the University of Kentucky. Dr. Andreatta received his PhD in Speech Physiology and Neural Science from Indiana University, Bloomington, and completed postdoctoral work in animal laryngeal neurophysiology at the National Institutes of Health. Dr. Andreatta serves as the director of undergraduate studies in CSD and teaches courses in the speech sciences, speech anatomy & physiology, communication neuroscience, rehabilitation neuroplasticity, and dynamic systems theory. Dr. Andreatta is a recipient of the University of Kentucky's Great Teacher Award and the UK College of Health Sciences Kingston Award for Teaching Excellence. Dr. Andreatta's research interests include sensory neuroscience of the human vocal tract, laryngeal muscle biology, and the neurophysiology of speech production. Dr. Andreatta lives in Lexington, Kentucky with his wife, children, and golden retriever.

# CHAPTER 2

# Basic Structure and Function of Neurons

*Richard D. Andreatta*

## Introduction and Learning Objectives

**Chapter 2** and the following chapter will focus on the structural and general functional factors characterizing the cells of the nervous system. While this topic may seem far removed from speech pathology and audiology, the reality is that an intuitive understanding of basic neurobiological principles and processes will allow you to more fully appreciate how major functional activities of the nervous system, such as motor control and perception, operate. Putting on my "*Mr. Obvious*" hat, speech, language, and hearing (S-L-H) all require brain function. Performing these behaviors adaptively to support human communication requires the coordinated activity of numerous brain regions underlying cognition, emotion, movement, and sensation. While it might seem satisfactory to simply know the major anatomical regions of the brain operating during S-L-H behaviors, it shouldn't be acceptable to you at all. We are living in an era where advancements in our understanding of the brain's functionality, interconnectivity, and adaptability are growing at an astoundingly rapid pace, with most of these leaps occurring in our comprehension of the brain's microstructure.

The operation of the nervous system as a whole, or what we generally describe in this textbook as "*behavior*," is based on the collective and cooperating function of tens of millions of individual cells. Without an introduction and foundation in cellular neurobiology, a complex-sounding term that simply means the study of how nervous system cells work, you will be left wondering why and how brain regions communicate with one another to produce their associated behavior. You'll also be left wondering how these same areas change their actions in light of rehabilitation after injury or disease.

Advancements in cellular neurobiology of the nervous system since the early 20th century have led to an explosion of knowledge about the roles that nervous system cells play in the complex creation and expression of animal behavior. We now understand that actions, thoughts, perceptions, remembered experiences, emotions, and virtually everything about who you are as an individual, or what you have ever experienced in your lifetime, are rooted in the cooperative activity of vast, interconnected networks of cells throughout the nervous system. Additionally, our understanding of the cellular bases of complex disease states and debilitating neurological disorders has expanded to a point where neuroscience is on the threshold of finding effective therapies for conditions such as Alzheimer's and amyotrophic lateral sclerosis (*Lou Gehrig's disease*). The cellular structure and function of the nervous system are thus a crucial body of knowledge for understanding its operation and the fundamental bases of behavior more fully.

I hope I've convinced you, or at least begun to persuade you, to take the time to learn about these basic cellular principles. The time and effort you spend learning about these ideas will be well worth it as we discuss other, more complex features of the nervous system. In this chapter, we'll focus on the **cytology** (*cell biology*) of the neuron, including its historical foundations, its general role in behavior, and its basic structure. After completing this chapter, you should be able to meet the following learning objectives:

- Explain the history behind the discovery of the neuron as the essential anatomical building block of the nervous system.
- Identify and describe the functional roles of different structural features of the neuron.
- Understand and explain the concept of population coding and how this mechanism helps form the nervous system's decision-making unit.
- Understand and explain the significance of the dendrite/soma to axon to dendrite/soma organization of information flow between connected neurons.
- Identify and define the functional and structural features of a neuron and glial cells.
- Describe the function and structural features of major neuronal organelles.

## Discovery of Two Classes of Cells in the Nervous System

The idea that body tissues are made up of individual units called cells seems remarkably obvious and a rather mundane fact by today's standards. However, it has only been in the last 200 years or so that our understanding of the cellular organization of life has even existed. The **cell doctrine**, the notion that animals are composed of small components called cells, was developed only in the early part of the 19th century. A little-appreciated fact about this doctrine, though, is that it was thought to apply to every part of the body *except* the nervous system. The exclusion of the nervous system from the cell doctrine was largely due to the lack of experimental methods to visually identify the complex structure of nerve cells in their entirety within living tissues. In fact, it took until the turn of the 20th century for neurobiologists to finally develop the methods needed to confirm that the nervous system, like all other body parts, was composed of individual cellular units. This accomplishment was by no means trivial. Realizing that the brain and the nervous system are composed of cells, just like all other body regions, began the era of neurobiological study in which we find ourselves today.

We can thank three influential neurobiologists—Camillo Golgi, Santiago Ramón y Cajal, and Charles Sherrington —who together were largely responsible for the needed technological advancements in nerve cell **histology** (*microscopic study of tissue structure*) that eventually springboarded the field into a new era of understanding. Golgi and Ramón y Cajal were chiefly responsible for developing novel methods to stain or dye nerve cells, revealing their complex shapes and extensive branching. Before these stains existed, the internal structure of the nervous system was a complete mystery because of the visual uniformity of brain tissue (*generally cream-colored and beige, with the consistency of loose Jell-O*) and the inability of the rudimentary microscopes of that era to focus clearly on cells with little image contrast. Imagine the excitement of early investigators upon seeing, for the first time, the enormous complexity and diversity of nervous system cells using newly developed staining techniques! Neurobiologists, at last, could identify not only the form of nerve cells but by using different types of staining methods, intracellular structures. Thus, the histological methods developed by these and other early neurobiologists helped establish critical structural and functional distinctions between cells of the nervous system and other cell types in the body.

This early histological work led to the discovery that the nervous system is composed of two distinct cell types: **neurons** and **glial cells** (Kandel et al., 2013). If the different parts of the nervous system were a cast of performers in a Broadway musical, neurons would definitely be the stars of the show, the divas that get all the attention and get to sing the best songs. Glial cells, on the other hand, would be the stage crew members working behind the scenes, trying to keep everything running smoothly.

Neurons (also called *nerve cells*) are highly excitable cells capable of generating and transmitting electrical signals over a wide range of physical distances. When I say, "*electrical signals*," I literally mean the same general form of electricity that runs your cell phone, your laptop, and the lights in a room, albeit on a much smaller scale. Neurons can change their electrical state rapidly in response to environmental changes. The quick shifting of electrical activity in a neuron is made possible by the presence of structures on the neuron's cell membrane that regulate the motion of charged particles, called **ions**, into and out of the cell (more on this in **Chapter 3**). In turn, neurons use these rapid electrical changes to trigger the release of chemical agents from within the cell to interconnect neurons and form functional networks (Hall, 1992). The moment-to-moment state of these interconnected neuron networks underlies all behaviors an animal can produce during its lifetime. We can thank the electrophysiological studies of Charles Sherrington for these fundamental insights because his work was central to the discovery of a nerve cell's communicative abilities at locations called the **synapse** (Kandel et al., 2013). (*A little historical fact:* Sherrington was the person who first introduced the term *"synapse"* to identify the physical communication point between neurons.) In short, neurons participate directly in all activities that we would describe and characterize as a "*behavior*" (Kandel et al., 2013).

In contrast to neurons, glial cells don't directly participate in signaling (*the transmission of information from one place to another*) but instead form a critical structural, insulating, and metabolic resource for neurons (Guyton & Hall, 2006). A silly way to remember the general role of glial cells is to think of them as bubble wrap used to protect and support fragile items when shipping a package. The importance of the structural and supportive roles of glial cells is reinforced by the fact that they significantly outnumber our signaling neurons. *Absolutely astonishing!* Even though the recognized roles of glial cells are backstage and not terribly glamorous, without them, the show could literally not go on. We'll elaborate on the functional and structural differences of neurons versus glial cells in much more depth in the next few sections of this chapter. For now, it's best to appreciate the major distinctions between these two cell classes in the nervous system: *Neurons signal information, while glial cells provide structural and metabolic support to neurons*.

## Neurons Are Made for Signaling and Communication

In this next section, we'll characterize the major structural and functional features of the neuron. The components we'll discuss are key to the way neurons obtain inputs, process information, and share that information with other neurons within highly interconnected collections or networks of cells.

A neuron possesses four functional zones and five associated structural features necessary to fulfill its role in signal propagation (*a term that neuroscientists frequently use to describe the "sending" of information over some distance*) and neuron-to-neuron communication. The structural or what we call the "*morphological*" features of a typical neuron are (a) **dendrites**, (b) **soma** or **cell body**, (c) **axon hillock**, (d) **axon**, and (e) the **presynaptic terminal**. As shown in **Figure 2–1A**, each of the structural features of a neuron is associated with a functional role that allows for the generation of different types of regional signals: an input site (*dendrites and soma*), a region for integrating or "mixing together" input signals (*axon hillock*), a conducting segment (*axon*), and lastly an output site (*pre-*

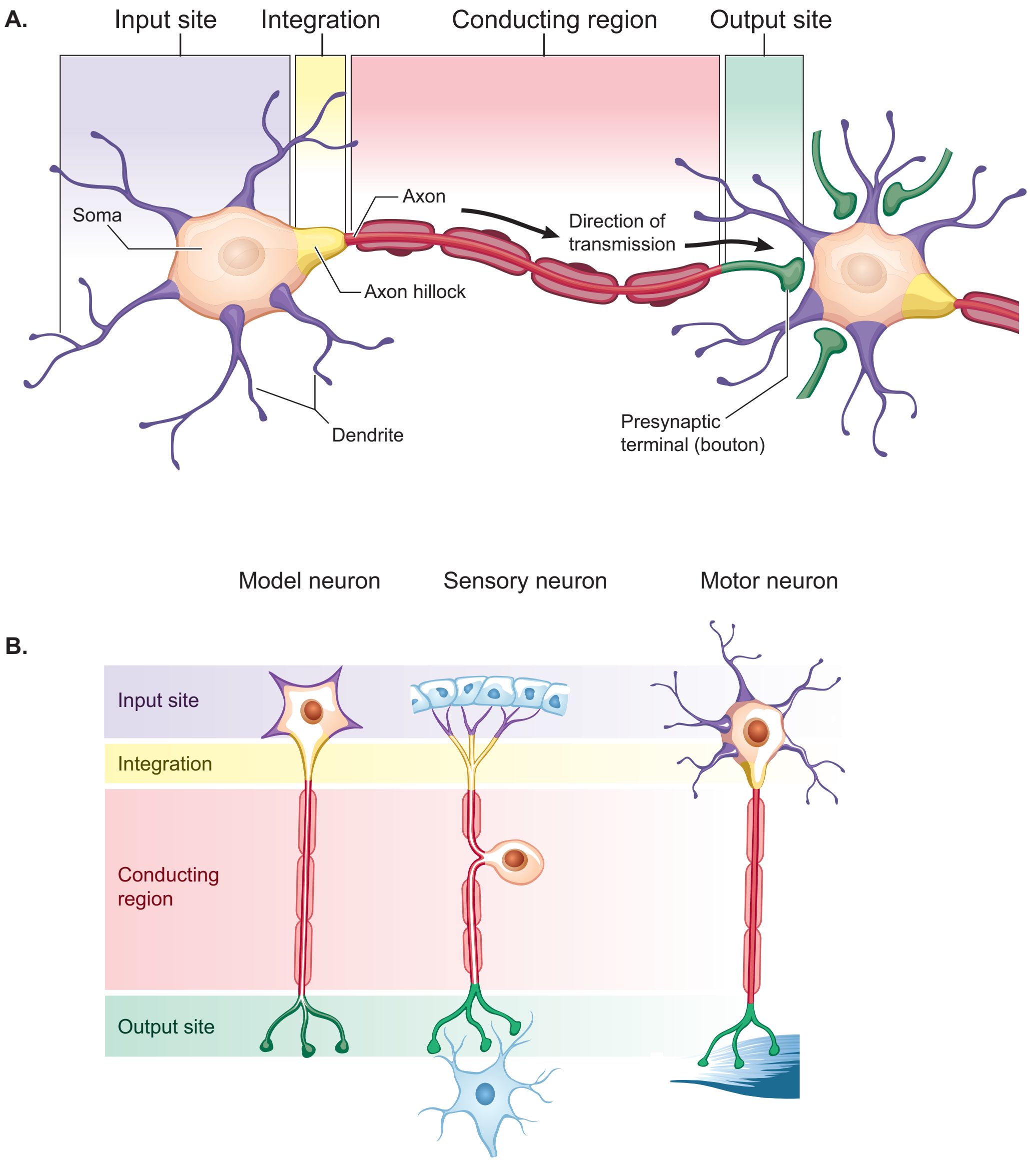


FIGURE 2–1. Basic structure and regional function of the neuron. **A.** A single multipolar neuron is shown synapsing to a target neuron. **B.** Both sensory and motor neurons exhibit regional functional specialization.

*synaptic terminal*). Regardless of whether we are talking about neurons that convey sensations or signals related to movement (**Figure 2–1B**), these structures and functional roles will form the basis for understanding how individual neurons operate to generate and change behavior (Carpenter, 1991).

## Neuronal Soma or Cell Body

The soma or cell body is the structural, metabolic, and genetic center of the neuron. From the soma, two major extensions of the cell membrane arise: the **dendrites** and the **axon**. Both structures can be thought of as highly specialized extensions of the soma, operating as the chief input and output sites of the neuron, respectively. Dendrites form complex, branch-like structures that receive information from the axons of other neurons and pass it to the soma. The axon, on the other hand, is often a single element extending from the soma and is dedicated to passing electrical signals to the dendrites and somas of other neurons downstream (see **Figure 2–1A** for an example).

All these principal structural components stemming from the soma are bound by the cell membrane or the neuron's **plasmalemma**. The terms *cell membrane* and *plasmalemma* can be used interchangeably for all intents and purposes. The plasmalemma forms a physical barrier between the extracellular environment and the intracellular cytoplasm of the neuron. As seen in **Figure 2–2**, the cell membrane is composed of molecules known as phospholipids arranged in two opposing layers, giving the plasmalemma its characteristic moniker of a **phospholipid bilayer**. The phospholipid molecule consists of a **hydrophilic** (*water-loving*) "*head*" and **hydrophobic** (*water-hating*) "*tail*." With these molecules arranged with their hydrophobic tails pointing inward and their hydrophilic heads facing the cytoplasm and extracellular fluid (*which happens to be mostly water*), you get an effective semipermeable barrier to most substances.

The bilayer arrangement of the plasmalemma is actually very useful and serves an important role in maintaining the contents of the neuron separate from the outside world. The bilayer is selectively permeable to substances wanting access through the membrane based on the composition of those substances. As you can predict, hydrophobic molecules can easily pass through the center of the cell membrane because they are just like the inside of the membrane. In contrast, hydrophilic substances are attracted to water but are blocked by the membrane's water-repelling core. These substances usually need help from special proteins, called *transporters*, to cross the membrane**.** While the plasmalemma of the neuron might seem like a necessary but albeit boring part of the cell, the truth couldn't be more different. The cell membrane is a key factor underlying the excitable nature of neurons and plays a critical role in the process of neural signaling.

Adding internal support to the soma and its associated extensions is the cytoskeleton of the cell. Much like we have a rigid skeletal framework supporting the soft tissues of our bodies, cells possess a cytoskeleton that functions in a similar manner. The cytoskeleton consists of three major classes of filament-like components: **microtubules**, **microfilaments**, and **neurofilaments**. These cytoskeletal structures are chiefly responsible for (a) defining the overall shape of a neuron; (b) adding internal structure to the soma, axons (see the axon cross-section inset in **Figure 2–3**), and dendrites; (c) anchoring complex proteins to the cell membrane; and (d) maintaining the distribution and placement of cellular organelles throughout the neuron.

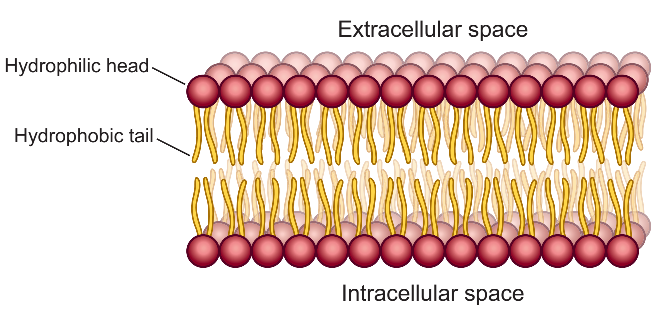


FIGURE 2–2. Phospholipid bilayer forms the cell membrane of the neuron. A bilayer is composed of molecules known as phospholipids, which consist of a hydrophilic head (phosphate) and hydrophobic tail (lipid). Bilayer configuration produces a semipermeable barrier because the hydrophobic tails of the phospholipid molecules are arranged pointing inward, while the hydrophilic heads face the watery cytoplasm and extracellular fluid.

## Axons and Dendrites

As mentioned earlier, the axon constitutes the output pathway of a neuron. Axons originate from a location on the soma called the axon hillock, a specialized segment that generates the action potential conducted down the axon. Axons can range in length from less than 0.1 mm to as long as 25 m—*the length of a blue whale!* The longest axons in the human body are roughly 1 m in length (*or closer to 1.5 m if you're the center for an NBA team*). Axons also vary in diameter, which has important consequences for the speed at which signals propagate along this structure. One of the largest diameter axons in an animal can be found in the deep-sea giant squid. Some of the axons controlling the siphon of this animal can measure 1 mm in diameter. That's about the thickness of a strand of cooked angel hair pasta and thus is clearly visible to the naked eye. While an axon is a single extension from the soma, it will divide into smaller branches called **axon collaterals** (see the green output site in **Figure 2–1B** for an example). Axon collaterals can appear at any place along the main axonal trunk but are most often seen toward its end as the axon approaches its target location (see **Figure 2–3** for examples). Axon collaterals from the main axon trunk help to distribute information from a single neuron to multiple output target locations simultaneously.

At the very end of an axon or axon collateral is where you will find the presynaptic terminal (*or* bouton*, if you prefer the fancier French term*). Axons and their presynaptic terminals lack major metabolic structures such as ribosomes and Golgi bodies, requiring the need for transportation mechanisms to ensure the distribution of proteins and other metabolic products to the presynaptic terminal (Kandel et al., 2013). Experiments during the 1940s first demonstrated that axon transport of substances, called **axoplasmic flow** or **transport**, is responsible for the shuttling of material from the soma to the presynaptic terminals (Weiss & Hiscoe, 1948). Axoplasmic transport mechanisms rely on microtubule "*rails*" and molecular "*feet*" to walk material at either fast or slow speeds down the axon to the presynaptic terminal. (*I always imagine this mechanism looking like loaded passenger cars running on a modern inverted and twisting rollercoaster, the kind you find at amusement parks like Disney World or Kings Island.*) The movement of material in the direction from the soma to the presynaptic terminal is called **anterograde transport**. When material from the presynaptic terminal must be sent back to the soma, a similar but alternative method called **retrograde transport** is used.

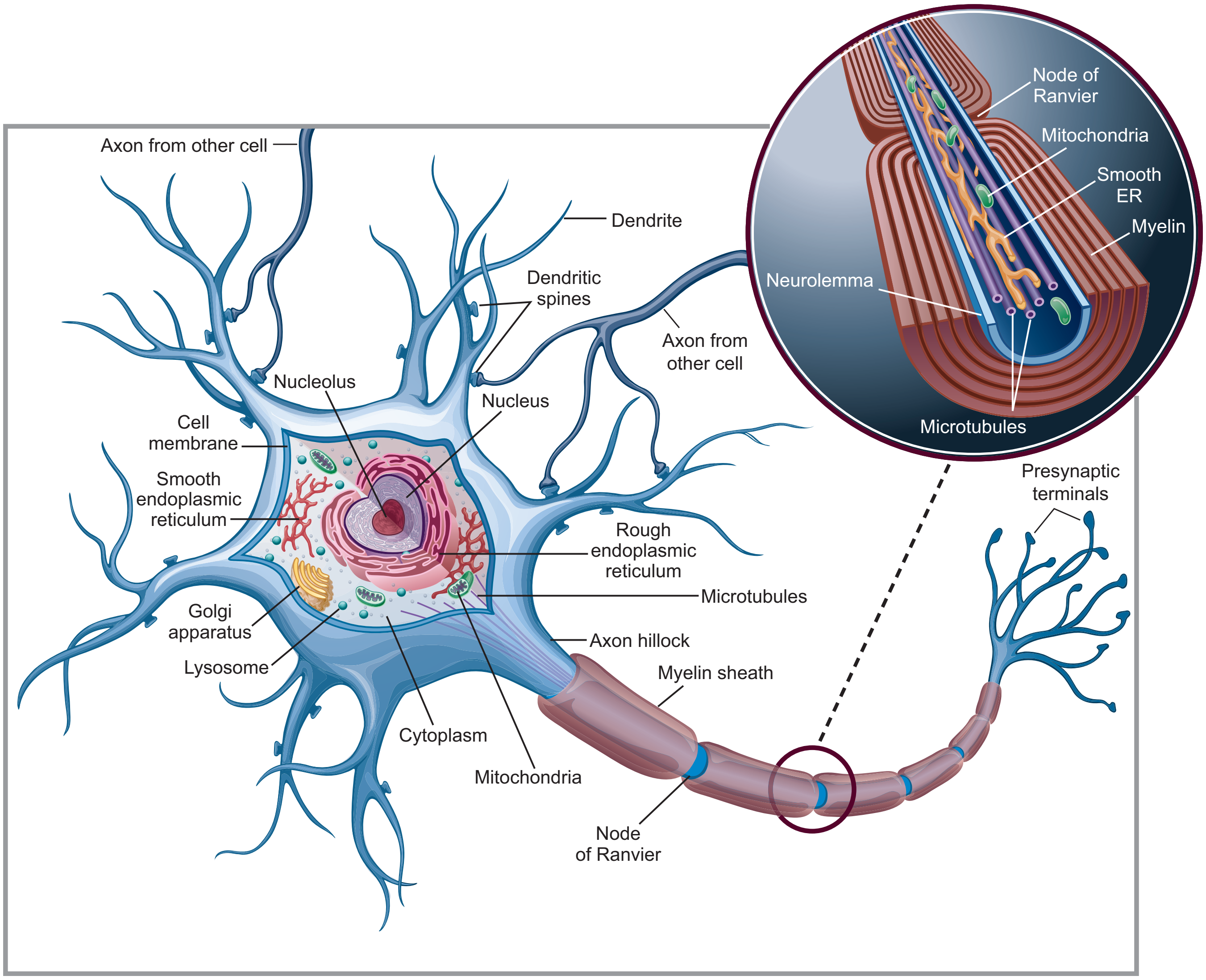


FIGURE 2–3. Cutaway perspective of a multipolar neuron showing the internal structure and major organelles.

The presynaptic terminal forms the first half of the communication mechanism between two neurons, known as the **synapse** (see presynaptic terminals illustrated in **Figure 2–3**). In a synapse, the cell conveying information is referred to as the **presynaptic cell**, while the cell receiving information is the **postsynaptic cell**. The presynaptic terminal contains virtually all the required chemical or electrical signaling machinery necessary to transmit an output to the postsynaptic cell (Hall, 1992). Presynaptic terminals can form synapses at three general locations on the postsynaptic cell: on dendrites, on somas, and even on an axon itself. Illustrated in **Figure 2–4** are three different arrangements of synapses that can be found in the nervous system. **Axodendritic** synapses are the most numerous and common form of synapse. In this type, the presynaptic terminal connects to the dendrites of the postsynaptic neuron. **Axosomatic** synapses are the second most numerous class and are formed between the presynaptic terminal of one neuron and the soma of the postsynaptic cell. Lastly, the **axoaxonic** variety (*as you can probably guess by its name*) is formed between two axons. This last form of synapse plays a critical role in regulating and modifying information transfer between two neurons, a process referred to as presynaptic inhibition.

The dendrite is the chief input site of the neuron and, as such, is covered with synapses. Many dendrites have small pier-like protrusions called **dendritic spines** where synapses are formed (see **Figure 2–3** for examples). Dendritic spines house numerous cellular mechanisms and organelles essential for modifying the synapse as a function of behavioral experience. While a typical neuron possesses a single principal axon, the number of dendrites a neuron has can vary tremendously (Hall, 1992). You can have neurons with so few dendrites,