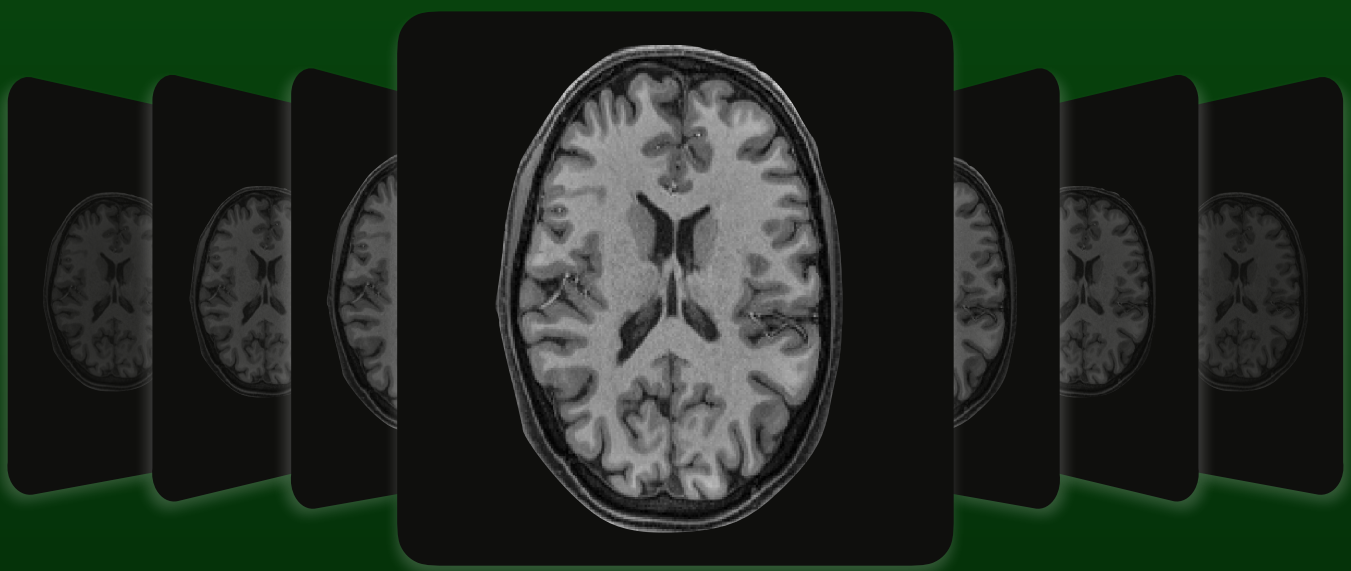
OXFORD NEUROIMAGING PRIMERS

Short introduction to

# Brain Anatomy for Neuroimaging



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PRIMER
APPENDIX

# List of Primers

***Series Editors:*** Mark Jenkinson and Michael Chappell

**Introduction to Neuroimaging Analysis**
Mark Jenkinson
Michael Chappell

**Introduction to Perfusion Quantification using Arterial Spin Labelling**
Michael Chappell
Bradley MacIntosh
Thomas Okell

**Introduction to Resting State fMRI Functional Connectivity**
Janine Bijsterbosch
Stephen Smith
Christian Beckmann

# List of Primer Appendices

**Short Introduction to Brain Anatomy for Neuroimaging**

**Short Introduction to MRI Physics for Neuroimaging**

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# Preface

This text is one of a number of appendices to the Oxford Neuroimaging Primers, designed to provide extra details and information that someone reading one of the primers might find helpful, but where it is not crucial to the understanding of the main material. This appendix specifically addresses the most essential elements of brain anatomy, as needed to work in neuroimaging.

We hope that this appendix, in keeping with the series as a whole, will be an accessible introduction to this topic - aimed primarily for those without a background in anatomy or neuroscience. Hence, we have concentrated on basic concepts rather than delving into any details. However, we also hope it is a good introduction to brain imaging terminology for those that might be familiar with anatomy but new to imaging. For physical scientists meeting anatomy for the first time we also include more references in the Further Reading at the end of the Appendix, though these are not necessary in order to understand the content of this Primer series.

This appendix contains several different types of boxes in the text that are designed to help you navigate the material or find out more information for yourself. To get the most out of this appendix, you might find the description of each type of box below helpful.

## Example Box

*Example box:* **Learning anatomy**

A very good way, either for beginners

This box directs you to the Oxford NeuroImaging primers website (www.neuroimagingprimers.org), where you will find examples that allow you to directly interact with data and perform practical exercises. These examples are intended to be a useful way to prepare you for applying these methods to your own data; but you do not need to carry out such exercises as you read through the primer. The examples are placed at the relevant places in the text, so that you know when you can get a more hands-on approach to the information being presented.

## Further Reading

**FURTHER READING**

The following is just a small

At the end, we include a list of suggestions for further reading, including both articles and books. A brief summary of the contents of each suggestion is included, so that you can choose the most relevant references for you. None of the material in this appendix assumes that you have read anything from the further reading. Rather, this list suggests a starting point for diving deeper, but is by no means an authoritative survey of all the relevant material you might want to consult.

Whilst the principles of MRI physics are well established and thus the material in this appendix will, we hope, be relevant for many years to come. Advances in the field of MRI acquisition continue and new techniques that acquire images with higher resolution, more quickly and with new information, appear all the time. Hence, all we hope for as authors is that this will be a useful introduction to what is a large and fascinating field of research that extends well beyond purely neuroimaging applications.

Mark Jenkinson and Michael Chappell

# Contents

# 1 Introduction

This appendix is a very simple and very short overview of gross neuroanatomy. If you have done any courses that touched on brain anatomy or physiology in the past, just skip this or skim through it very quickly—but have a look at the information more specific to neuroimaging (such as the terminology related to image views) in section 3 if you have not previously worked with images. The intended readership for this appendix is someone without a back- ground in biological sciences beyond school level (e.g., many mathematicians, engineers, and physicists), and its aim is to introduce some basic concepts and terminology that will help you understand the material in this and other primers.

# 2 Brain cells and tissues

There are several different types of cells present in the brain, but the most well known and most interesting (for most of us) are the "little gray cells"—that is, the ***neurons.*** Neurons are highly interconnected and their electrical activity is what underlies all actions and mental processes. In addition to the neurons there are also glial cells, blood vessels, membranes, and fluid that support the neurons both structurally and nutritionally.

Each neuron has an ***axon***, which transmits the output of the cell. The axon is the longest component of the cell, being anything from a fraction of a millimeter to hundreds of millimeters long. The axon is connected to the neuronal body (the soma), and the neuronal body accumulates inputs through an array of ***dendrites***, which connect it to a large number of other neurons via ***synapses*** (points where the axon terminal and the dendrites connect). See Figure 1 for an illustration.

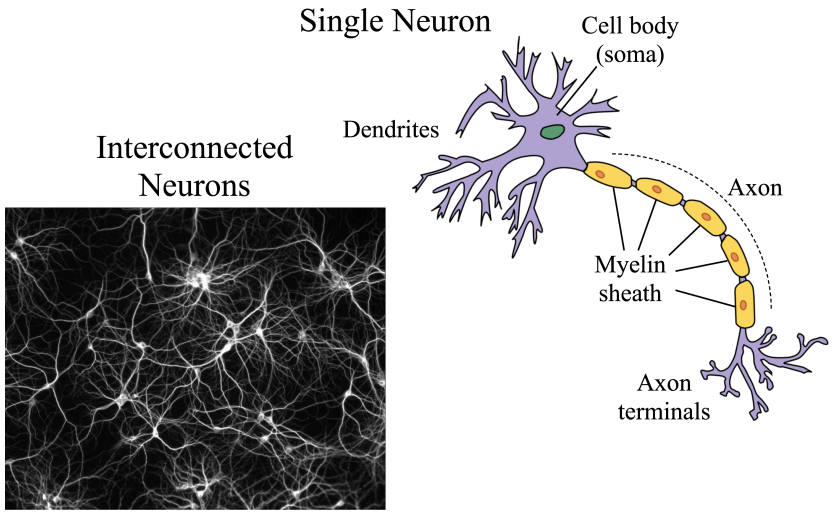


**Figure 1:** Schematic of a neuron (top right), showing the constituent parts, especially the cell body (soma), the dendrites, the axon, and the myelin sheath. Neurons are very densely connected together via synapses between axon terminals and dendrites, as shown in the image (bottom left).

Within the brain, most axons are surrounded by insulating layers of ***myelin***, also known as the ***myelin sheath***; the myelin is created by cells called oligodendrocytes. This myelin covering is made from a fatty substance and greatly improves the transmission of electrical signals down the axons. The breakdown of myelin is a major factor in several neurodegenerative diseases.
The diameter of a typical axon is of the order of one micrometer (1 µm), although this varies with the type of neuron, while the neuronal cell bodies are an order of magnitude larger. However, as the resolution of a structural MRI scan is typically 0.5 mm to 1 mm, we cannot resolve individual cells and we have a view that is similar to what can be seen by looking at an individual brain with the naked eye. At this resolution there are two obvious types of gross brain "tissue": ***gray matter*** and ***white matter***. The gray matter is mainly comprised of neuronal cell bodies, though it contains a mixture of other cells and structures (e.g., some axons, glia, blood vessels, membranes), while white matter is mainly comprised of axons, often collected together in ***axonal fiber bundles***, but, again, a mixture of some other cells and structures is present. White matter gets its name from the fact that it is the tissue with the lightest color when seen in a postmortem brain; this is due to the fatty content of the myelin. In addition, we commonly refer to ***cerebrospinal fluid*** (CSF), for convenience, as the third "tissue" type in the brain, though really this is just fluid and not an actual tissue. See Figure 2 for an illustration.

These "tissues," although they seem visually distinct, are a simplification of the microstructure. For instance, different relative proportions of axons and neuronal bodies exist in various regions, as well as different subtypes of neurons (e.g., pyramidal neurons); so there is variation within both white matter and gray matter across the brain. This variation is particularly pronounced in the deeper structures (e.g., the thalamus), as these tend to have a higher proportion of axons to neuronal bodies than other areas of "gray matter" in the brain. Nonetheless, these "tissues" are a very widely used and convenient concept in both gross anatomy and MRI.
That is all we will say here about these tissues and cells; we will not discuss glial cells, blood vessels, and other structures (e.g., meninges, choroid plexus, falx cerebri) although it is useful to keep in mind that there are a variety of cells and structures in brain tissue beyond neuronal bodies and axons. A great deal is known about these various cells and structures, but we will not discuss any of it here, as this introduction is intended to give you the essential information that you will need in order to do neuroimaging analysis.

# 3 Navigating around brain images

Besides knowing something about the small scale of the biological constituents of brain tissue, it is also important to have some knowledge about how to navigate around the brain at the large scale. To start with, we will consider how directions in the brain are named, as in neuroimaging you will encounter these terms regularly. There are, unfortunately, two standard naming conventions that are applied to the brain and both are in active use, so you need to be familiar with both.
The terms that name the major anatomical axes within the brain, in one convention, are ***superior–inferior, anterior–posterior, and left–right*** (or S-I, A-P, and L-R for short). In the other convention the equivalent terms are respectively ***dorsal–ventral, rostral–caudal, and left–right***. See Figure 3 for an illustration of these directions in the human brain. For those of you who are not Latin scholars, the second set can be harder to remember; you may find it helpful to think of dorsal fins of a fish, dolphin, or shark being at the top and of the word "rostral" as rhyming with "nostril." In addition to

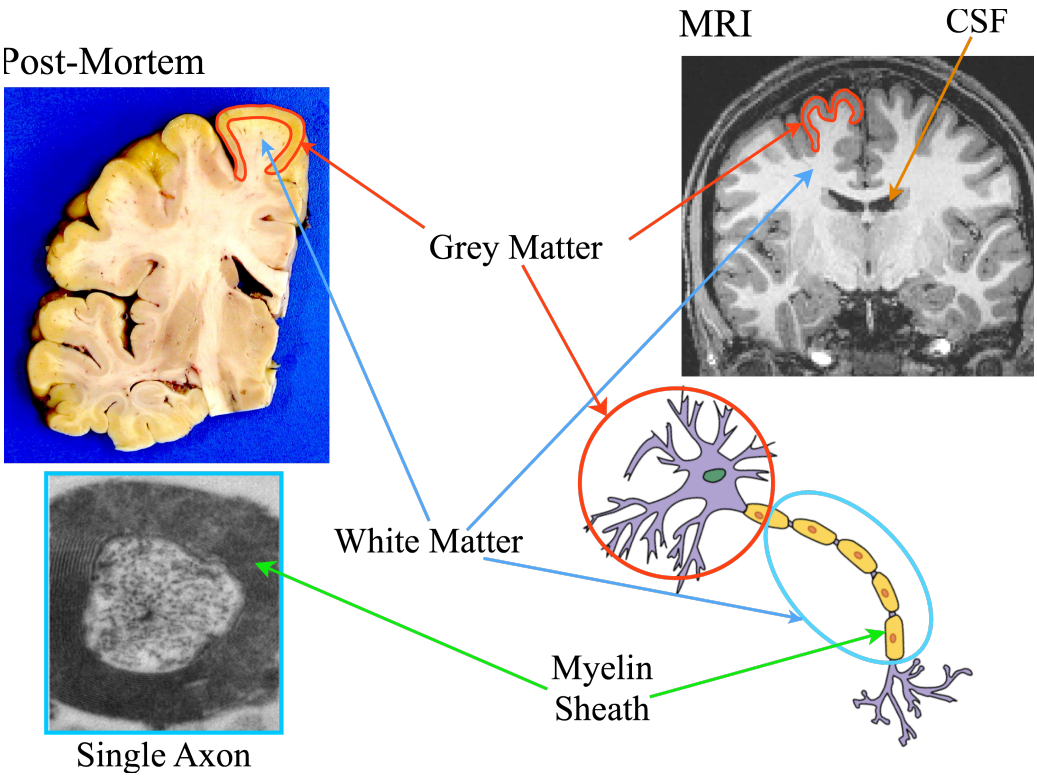


**Figure 2:** Illustration of gray matter and white matter tissues in a postmortem brain section (top left) and in an MRI (top right), together with how they relate to the neuronal cells (bottom right). The white matter is predominantly full of axons, each surrounded by a myelin sheath (bottom left).
Left panel: Reproduced under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0). Source: Liu XB, and Schumann CM (2014). "Optimization of electron microscopy for human brains with long-term fixation and fixed-frozen sections," *Acta Neuropathologica Communications*, Volume 2, Issue 42, DOI: 10.1186/ 2051-5960-2-42, Copyright © 2014 Liu and Schumann. Right panel: Reproduced under the terms of the Creative Commons Attribution-Share Alike 3.0 Unported license. Source: "Anatomy and Physiology" by the US National Cancer Institute's Surveillance, Epidemiology and End Results (SEER) Program, https://training.seer.cancer.gov/

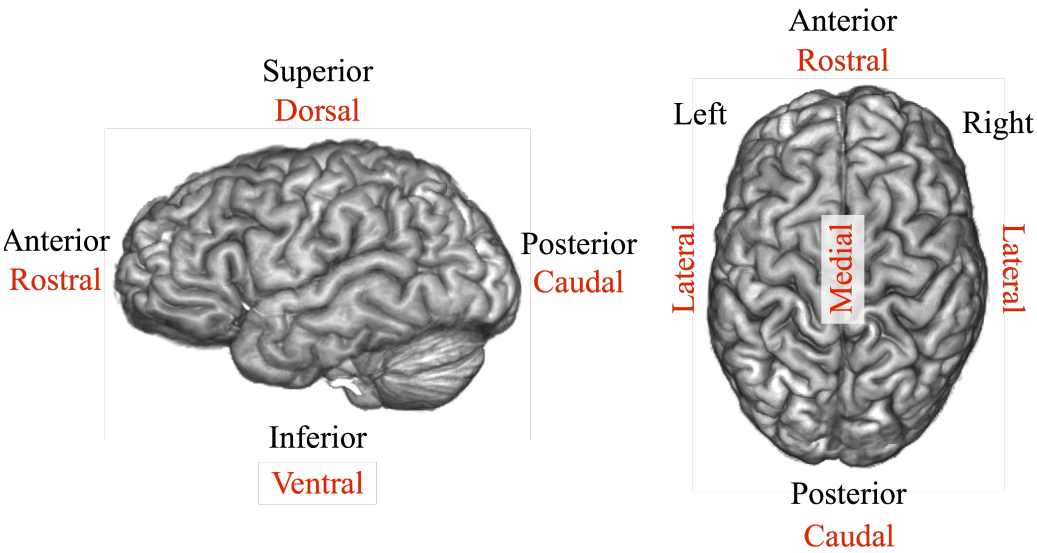


**Figure 3:** Illustration of the main anatomical axes of the brain, showing both sets of terms; each set is commonly used and hence worth memorizing.

these axes, there is also the term ***lateral–medial*** for describing whether locations are near a side edge (lateral) or near the center (medial).

In imaging we also commonly use standard terms for the different planes that are used to virtually slice through the brain (in neuropathology labs the slicing is more literal). The terms for these planes are ***coronal*** (showing superior–inferior and left–right), ***sagittal*** (showing superior–inferior and anterior–posterior), and ***axial***, ***horizontal***, ***transverse***, or ***transaxial*** (showing anterior–posterior and left–right). These are illustrated in Figure 4. In this figure the planes are shown at a fairly standard orientation, but it is also possible to have imaging planes at other angles and, when a plane is very different from the ones illustrated (e.g., when an axial plane is tilted by 30–45° toward the coronal plane), it is described as ***oblique***, though such cases are relatively rare.
It is also worth noting that, when displaying 2D slices, there are two different conventions for the orientation that are commonly used: ***radiological*** and ***neurological***. These terms refer purely to the way the left and right sides of the brain are displayed (on a screen or on paper), the neurological convention having them consistent with the viewer's perspective (i.e., left on the left), whereas on the radiological convention they are flipped (i.e., left on the right). The reason why these exist is historical and based on whether they reflect the view that you would have of the brain (head) if facing a person as opposed to standing behind them (see Figure 5). Neuroimaging did not invent either of these conventions—they come from medical practice— but we are stuck with them. In the literature you will see both conventions used, and hence it is very important to label your images "L" and "R" if the reader needs to know what convention you are using.

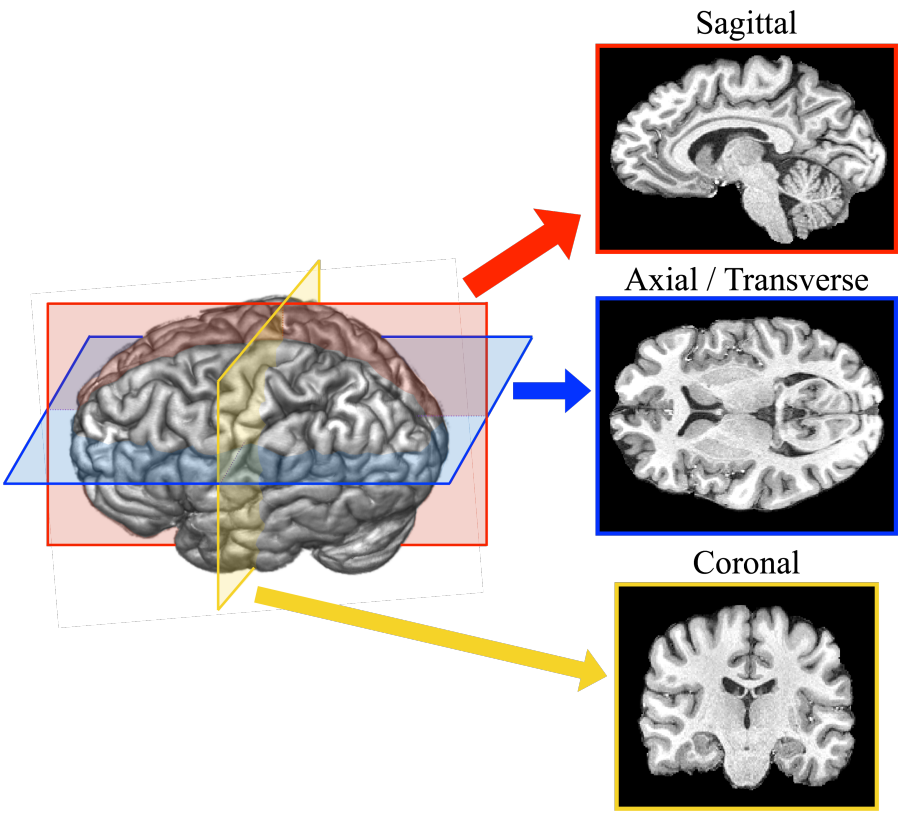


**Figure 4:** Illustration of the anatomical axes of the brain and of the three cross-sectional planes that are very commonly used in imaging.

Other useful terms for navigating around the brain at the large scale are associated with the major lobes. The names for these lobes are ***frontal***, ***occipital***, ***parietal***, and ***temporal*** (see Figure A.6). Although they are easy to distinguish in nice colored images, finding the boundaries between them on an individual brain varies between easy (e.g., between the temporal and the frontal lobes) and highly difficult (e.g., between the parietal and the temporal lobes) and determining them requires some experience. These lobes are very common and their names are very useful for navigating around the brain, as a lot of the more specific names are really just compound terms made from them and the anatomical axes. For example, the dorsolateral prefrontal cortex (or DLPFC) is an area that is in the top (dorsal) and outside (lateral) part of the start (pre-) region of the frontal lobe (that is, in the most anterior part of the frontal lobe). It is worth spending a little time to become familiar with all the terminology in this section, as this will help you a lot with understanding what other people are talking about and what is written in the literature. It certainly does not cover everything, but it is the most important basis to start with.

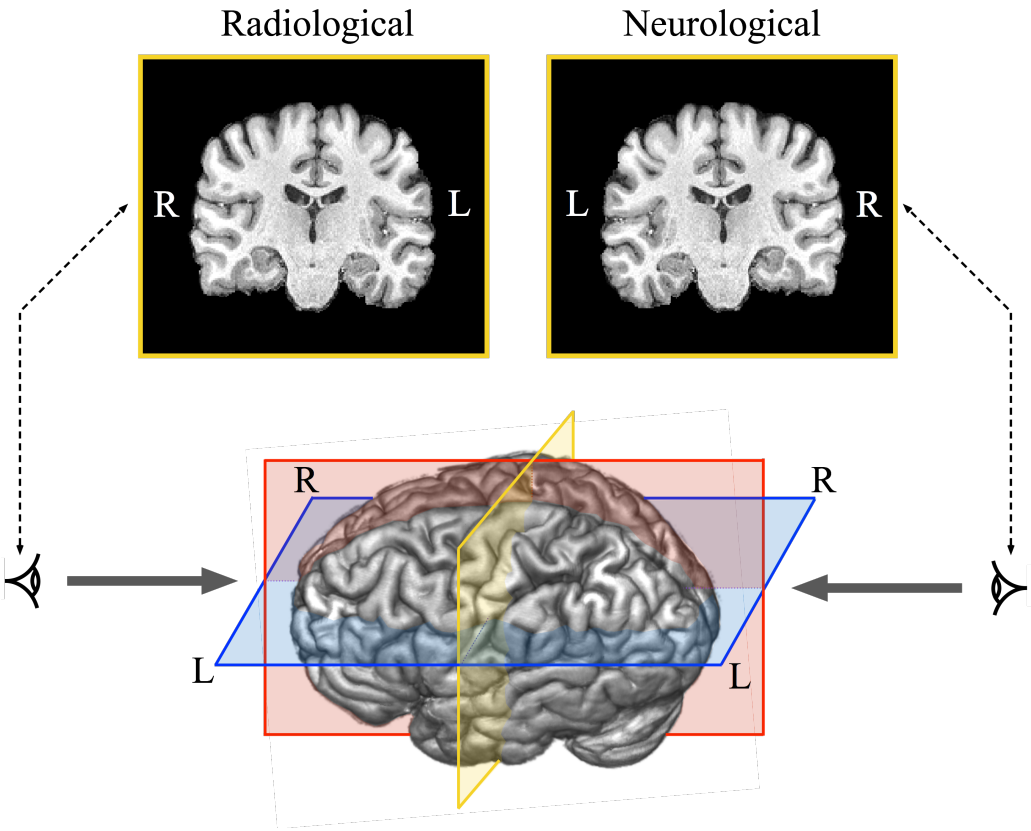


**Figure 5:** Illustration of radiological and neurological conventions for viewing images, which are originally based on whether the brain is viewed from the front (radiological) or from behind (neurological). The labeling "L" and "R" in the images is necessary for making it clear which convention is being used when showing images.

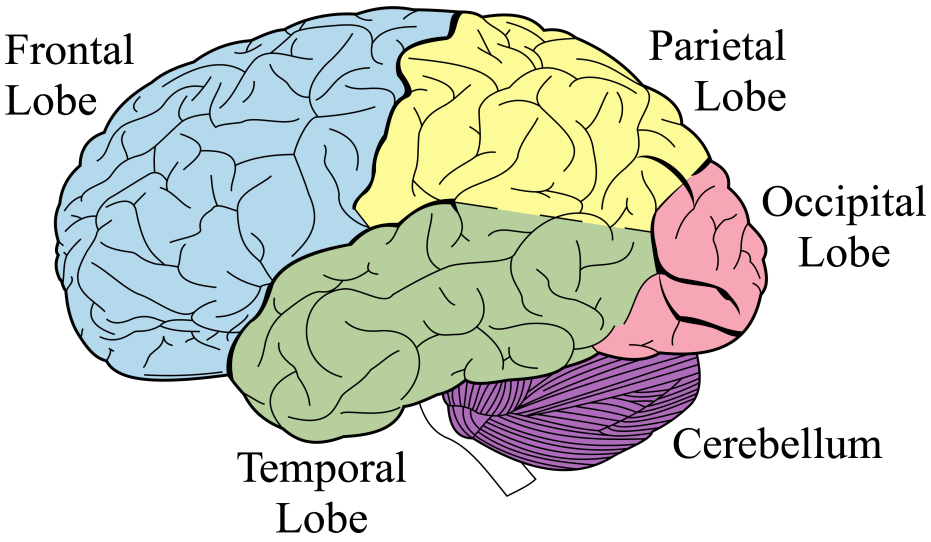


**Figure 6:** Illustration of the four main lobes of the human brain and of the cerebellum. Reproduced from Gray H (1918) ***Anatomy of the Human Body***, 20th Edition, Warren H. Lewis (ed.), Philadelphia and New York: Lea and Febiger.

# 4 Brain structures

There are a lot of finer, more detailed, structures and terminology associated with brain anat- omy. However, learning about all of these is not necessary in order to start in neuroimaging. You will soon become familiar with the structures that are of the greatest relevance to your own area of interest and to that of your closer colleagues. That being said, we will now discuss a set of ***very*** common terms and structures that it is helpful to know a little about.

The most essential and general structures[1] to know about next are the lateral ventricles, the spinal cord, the brainstem, the cerebral cortex, the corpus callosum, and the cerebellum. A very brief description of these structures is given here, as well as in Figure 7, which depicts where they are in the brain.

- The ***lateral ventricles*** are the main fluid-filled spaces in the middle of the brain, where the fluid is CSF. These usually provide the most obvious visual indication of brain atrophy (brain tissue loss due to typical ageing or pathology), as the ventricles increase in size to take up the extra volume due to fluid pressure.
- The ***spinal cord*** is primarily a collection of axonal fibers linking the brain to the rest of the body and running from the base of the brain down the spinal column. It also contains areas of gray matter and not only acts as a relay of signals from the brain and peripheral nerves but also does some basic processing of the signals itself.

[1] Consensus will never be reached on such lists, so apologies to anyone who has a favorite structure that did not make it into this section.

- The ***brainstem*** is a medial structure at the base of the brain, continuous with the spinal cord, and contains substantial amounts of white matter and gray matter, organized into various smaller structures or nuclei.
- The ***cerebral cortex*** is the outer layer of gray matter that covers most of the human brain and, roughly speaking, represents higher level cognitive functions in the human (less evolved brains have less of it). This layer is typically between 2 mm and 5 mm thick, primarily consisting of neuronal cell bodies (though it contains some strongly myelinated areas as well, such as the stria of Gennari) and the whole cortex is very highly folded. Each fold consists of a ***gyrus*** (the top/crown/crest/ridge of the fold) and a ***sulcus*** (the bottom/pit/valley/depression/furrow/fundus); see Figure 7. Certain gyri and sulci (these are the plural forms) are useful landmarks or have special roles. However, due to the large variability in folding patterns between individuals, not all gyri or sulci have specific names, which is why the large-scale terminology of directions and lobes is still very useful.
- The ***corpus callosum*** is an obvious white matter structure, easily seen on a medial sagittal slice, sitting on top of the lateral ventricles. It is a large array of axons that constitute the primary connections between the two hemispheres (halves of the brain).
- The ***cerebellum*** or "little brain" is a structure that sits underneath the occipital lobe and is like a mini version of the cerebral cortex, having an outer layer of gray matter that is very highly folded and white matter tracts running within, which connect it to the rest of the brain.

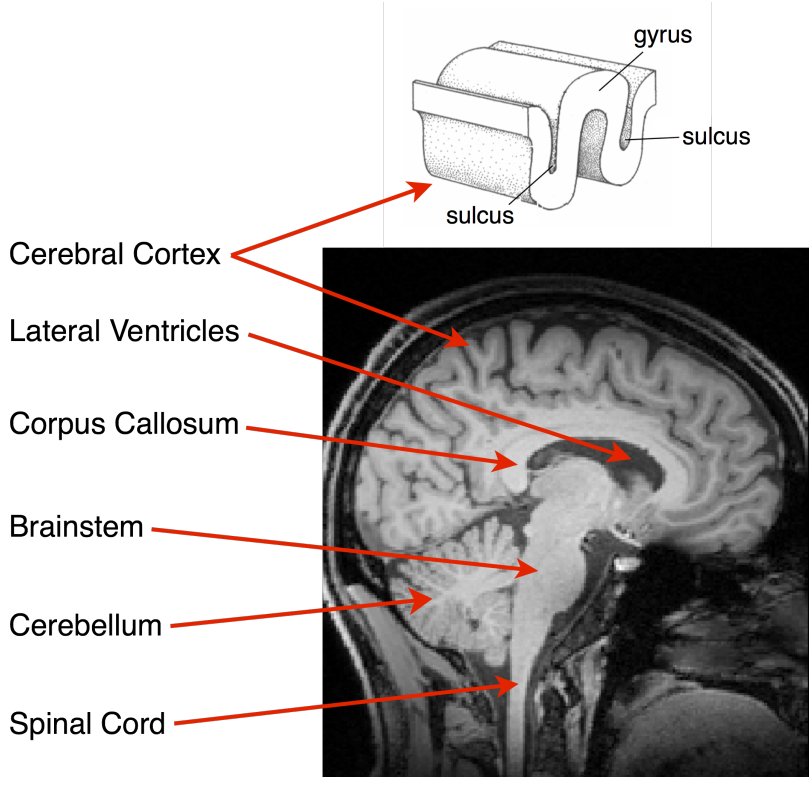


**Figure 7:** Illustration of some of the main features of brain anatomy. At the top is a diagram showing a small section of the 3D folded gray matter cortex.
Contains material that has been released into the public domain. Source: Albert Kok.

In addition to these structures there are some very notable subcortical structures that will be mentioned in the primers. These are the thalamus, the hippocampus, the amygdala, the putamen, the globus pallidus (or the pallidum), the caudate nucleus (or the caudate), and the nucleus accumbens; see Figure 8. They are also referred to in groupings (e.g., the striatum or the basal ganglia) or in terms of subdivisions (e.g., internal and external parts of the globus pallidus). Their anatomy and function are complicated, but they have prominent roles in brain function and structure, especially in disease, and so it is useful to have at least a passing familiarity with their names.

After this, things get more and more detailed. For instance, a set of anatomical areas, or ***parcellation***, of the cortex that is commonly referred to is the set of ***Brodmann areas*** (BA), though these are based on cytoarchitecture (microscopic cellular structure) and are not easily or accurately defined on MRI. Nonetheless, Brodmann areas are well-known structures in brain anat- omy and you are likely to come across at least some of them. The good news is that it is not necessary to go into details about further anatomical terms and definitions at this stage, and some are likely to remain relatively unfamiliar, depending on the areas that you work with most. If you are new to neuroscience, we recommend that you consult one of the texts listed in the Further Reading section at a later date in order to get a better overview and understanding of brain anatomy and to use the digital atlases in order to learn about them (see Example Box "Learning anatomy with digital atlases").

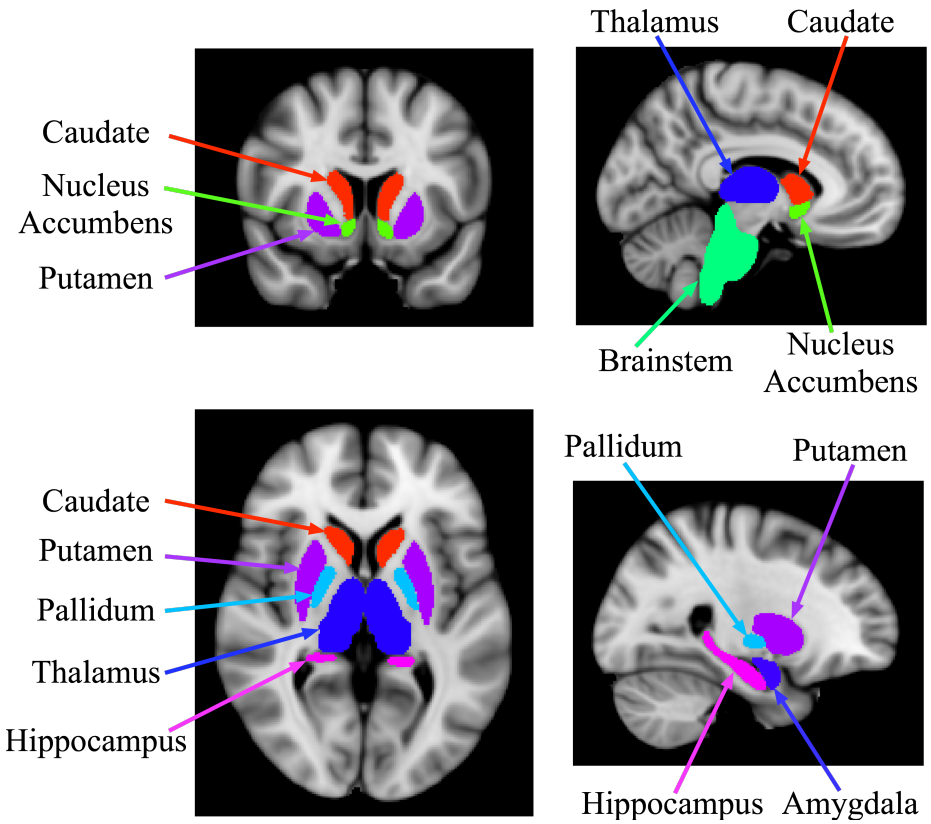


**Figure 8:** Illustration of some common subcortical structures.

### *Example box:* Learning anatomy with digital atlases

A very good way, either for beginners or for experienced researchers, to learn about brain anatomy and to delve into more details is to use existing digital atlases. These are available in all major neuroimaging software toolsets; but they are usually generated by independent research groups. The structures and details depicted in each atlas are different and each atlas normally concentrates on a particular aspect of brain anatomy or on a technique used to derive the information. The kinds of techniques that are used include manual tracing of MRI scans by experts; histology results aligned to MRI; and data-driven imaging results derived from diffusion or functional parcellation methods. Each technique brings with it certain advantages and disadvantages in terms of what determines the boundaries between areas and what kind of areas are included. For example, the Harvard–Oxford atlas is based on probabilistic averaging of expert manual tracings of MRI scans of a group of subjects; hence it is driven by features in the MRI scans, combined with some higher level expert knowledge about structure shape, as not all boundaries are clear on an MRI scan. In contrast, the Jülich histological atlas is based on probabilistic averaging of multisubject postmortem cyto- and myelo-architectonic segmentations, while the Oxford thalamic connectivity atlas is based on probabilistic averaging of parcellations calculated using diffusion tractography.

On the primer website you will find instructions for viewing several different atlases and ways to explore them. We strongly recommend this for people new to the field; and we suggest that the more experienced researchers also take a quick look, as the number of available atlases and tools for interacting with them improve over time.

## SUMMARY

- The three main “tissue” types in the brain are: gray matter, white matter, and CSF.
- Gray matter and white matter are actually a complicated mixture of cells and other structures, and variations exist within each tissue.
- There are two naming conventions for large-scale directions in the brain superior–inferior or dorsal–ventral; anterior–posterior or rostral–caudal; left–right; lateral–medial.
- The main imaging planes are sagittal, coronal, and axial.
- The main brain lobes are frontal, temporal, parietal, and occipital.
- Be aware that there are many structures and areas in the brain and that it is difficult to identify some cortical areas, given individual variability in the folding patterns.
- Digital atlases are a great tool for improving your knowledge of anatomy and of how it relates to MRI scans.

## FURTHER READING

The following is just a small sample from the many excellent texts available in the field of neuroanatomy, including several that had personal recommendations from our colleagues.


- Swanson, L. W. (2012). Brain Architecture: Understanding the Basic Plan. Oxford University Press.
- Nolte, J. (2008). The Human Brain: An Introduction to Its Functional Anatomy (6th ed.). Elsevier.
- Siegel, A., & Sapru, H. N. (2011). ***Essential Neuroscience***. Wolters Kluwer Health/Lippincott Williams & Wilkins.
- Martin, J. H. (2012). Neuroanatomy Text and Atlas (4th ed.). McGraw-Hill.
- Bear, M. F., Connors, B. W., & Paradiso, M. A. (Eds.). (2007). ***Neuroscience*** (Vol. 2). Lippincott Williams & Wilkins.
- Gould, D. J., & Brueckner, J. K. (2007). Sidman's Neuroanatomy: A Programmed Learning Tool. Lippincott Williams & Wilkins.