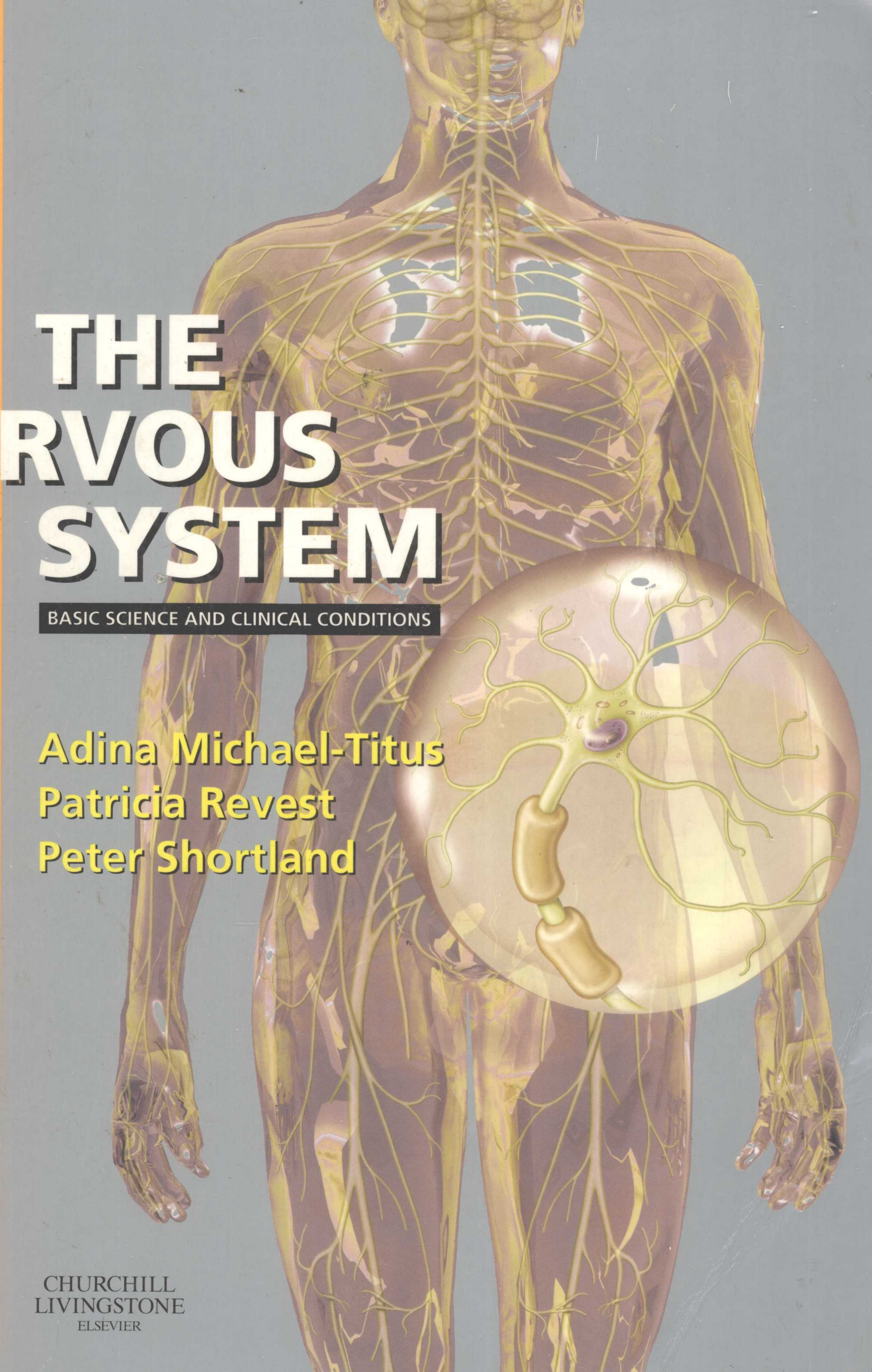
SYSTEMS OF THE BODY

THE NERVOUS SYSTEM

BASIC SCIENCE AND CLINICAL CONDITIONS

Adina Michael-Titus
Patricia Revest
Peter Shortland



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PREFACE

The diseases of the nervous system represent one of the most important challenges in modern medicine. Medical schools worldwide have adopted various strategies in the teaching of neuroscience. One of the more recent approaches combines anatomy, physiology and pharmacology, in order to achieve an integrated view of the various pathologies. The problem-based learning method in medicine is based on this concept of integration.

This book is part of the Systems of the Body series, which has been designed to provide a teaching tool for medical curricula that use problem-based learning. The aim of our book is to cover the basic science required to understand the structure and function of the nervous system, and its major pathologies, at a level appropriate to medical students in the first years of training. The volume comprises two parts. The early chapters offer an introduction to the general organisation of the nervous system, and the cellular and molecular mechanisms that govern its function. A separate chapter is devoted to the clinical examination of the nervous system. The later chapters, which form the main body of the book, are built around clinical cases. The chapters start with clinical scenarios, which prompt an exploration of specific issues, thus allowing us to introduce and discuss the knowledge that is required for the diagnosis and treatment of the conditions presented. Each of these chapters ends with another clinical case, relevant to the topic under consideration. This second case, and the additional questions provided, can be used by students for self-assessment.

Our experience of teaching medical students guided us throughout the writing of this text, and we tried to present complex concepts in an accessible and clear manner. Our wish was not only to present the facts, but also to increase the students' awareness of the many unresolved issues in neuroscience. It is our hope, therefore, that this book will not only assist students in the learning process, but also stimulate their interest and enthusiasm for the fascinating field of neuroscience.

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Last, but certainly not least, we thank our families and friends for their constant affection and support, which makes everything possible and worthwhile.

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ORGANISATION OF THE NERVOUS SYSTEM

1

SYSTEMS OF THE BODY

Chapter objectives

After studying this chapter you should be able to:

① Describe the basic organisation of the peripheral and central nervous systems.

② Name and identify the major nervous system structures and describe their primary functions.

③ Describe the organisation and functions of the autonomic nervous system.

Introduction

The nervous system, which consists of the brain, spinal cord and peripheral nerves, is a highly specialised and complex structure. It is an information-processing system that regulates all the physiological functions of the organism. In addition, the nervous system performs unique functions that operate independently of other systems in the body. These underlie consciousness, memory, rationality, language, and the ability to project our mental images forwards or backwards in time. Representations of the external world are transmitted, transformed and manipulated by the nervous system to subsequently affect behaviour. Thus, the nervous system has four important functions:

1. sensory (gathering of information from the external environment)
2. integrator (of information from all sources for assessment)
3. effector (to produce a motor response)
4. internal regulator (homeostasis for optimum performance).

The net results of all these functions are as follows: first, the creation of a sensory perception of the external world; second, behaviour; and finally, the creation of knowledge that can be used to guide future behaviour in response to changes in the surrounding environment.

In order to appreciate how the nervous system produces behaviour, it is necessary to understand how it is organised functionally and anatomically. The experience of examining a brain is very much like the experience of buying a car. Before buying a car, you inspect it and then take it for a test drive to make sure that it operates normally and runs smoothly without faults. Then you open up the bonnet to look at the engine. Unless you happen to be a trained mechanic or have an interest in car engines, you might be able to name a few parts, e.g. the radiator, the battery and the fan belt, but not the rest of mass of wires, spark plugs and assorted boxes. Moreover, knowledge of the name does not always indicate what the function is, or how all the different parts combine to burn petrol to make the car run. It is the same with the nervous system; you may be able to name some of the parts, such as the cortex, cerebellum and brainstem, and have a rough idea of what some of the different parts do, but have little idea of how they accomplish a task such as reading this sentence. And when the car breaks down, we call the automobile rescue services. When the nervous system breaks down or misfires, we call in the neurologists, neurosurgeons or psychiatrists.

Although the anatomy of the nervous system appears complex and daunting, its organisation is governed by a set of relatively simple developmental, organisational and functional rules that bring order to it. The functional rules are summarised in Table 1.1.

The aim of this chapter is to provide a 'service manual' for the nervous system, i.e. to give a functional overview of the neuroanatomy of the brain, spinal cord and nerves. To do this, it is necessary to consider the basic parts of the nervous system, and to identify what they do and how they are related. Finally, we can see how the different parts interact, using the principles outlined in Table 1.1, to produce behaviour.

The nervous system comprises two parts: the peripheral nervous system (PNS) and the central nervous system (CNS). These two systems are anatomically separate but are functionally interconnected and integrated (Fig. 1.1). The PNS consists of nerve fibres that transmit specific sensory and motor information to the CNS, which comprises the spinal cord, brainstem and brain. The CNS is housed within the bony structures of the vertebral canal and skull, for protection. Additional mechanical buffering protection of the CNS is afforded by the surrounding meninges and ventricular system.

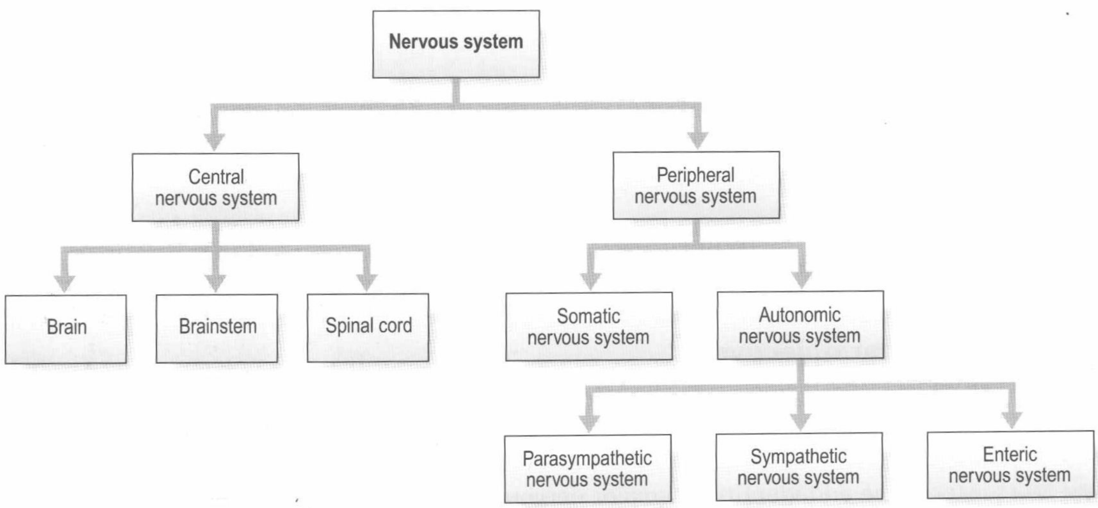


Fig. 1.1
Overview of the anatomical organisation of the nervous system.

Table 1.1
Principles underlying the functioning of the nervous system

Behaviour is produced by processing of information in a sequence of 'in → integrate → out'
Separate sensory and motor divisions exist throughout the nervous system
The nervous system has multiple levels of function
The nervous system is organised both in parallel and in series
Most neural pathways relaying information decussate from one side of the central nervous system to the other
The nervous system regulates activity through excitation and inhibition
There is both symmetry and asymmetry in brain anatomy and function
Some of the functions of the brain are located in specific regions of the brain, while others are distributed

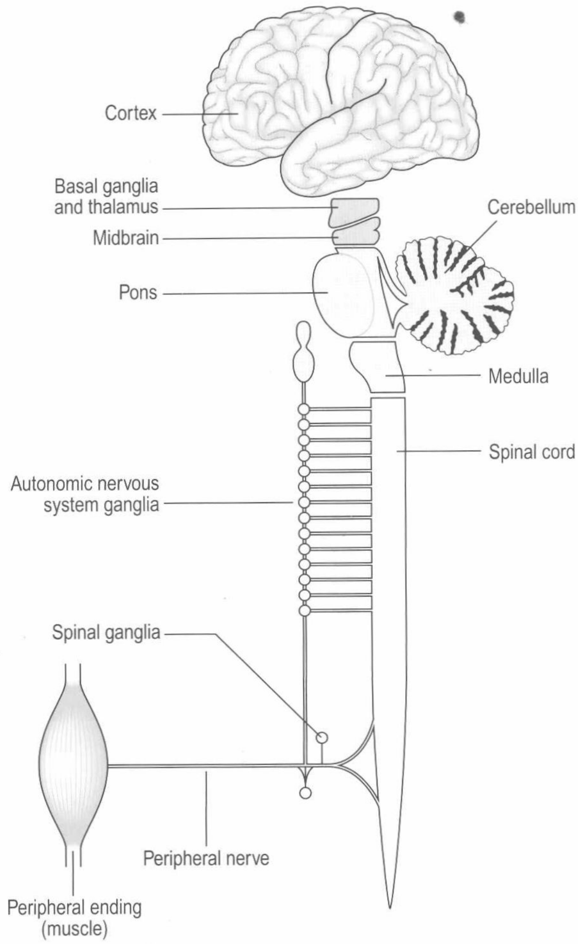


Fig. 1.2

Major parts of the nervous system. Light shading: structures of the supratentorial level. Dark shading: structures of the posterior fossa level. No shading: structures of the spinal level

Overview of brain anatomy

The CNS comprises six anatomical regions: the cerebral cortex, the diencephalon (thalamus and hypothalamus), the midbrain, the pons and cerebellum, the medulla, and the spinal cord (Fig. 1.2). The best way to understand the anatomy is to look at the external and internal topography, to identify anatomical structures and their relationships, and then to define the functions of the identified structures.

Meninges

To continue with the car analogy, if we 'open the bonnet', i.e. the skull, and look inside, the first thing seen is the membranes that cover the brain, called meninges. These membranes surround and protect the CNS. There are three layers: the dura mater, arachnoid and pia mater. These layers and their functions are described in more detail in Chapter 12.

The dura mater forms folds that separate different brain regions from each other. The cerebral falx separates the two cerebral hemispheres and becomes continuous with the cerebellum tentorium in the midline. This latter structure covers the posterior skull fossa and separates the cerebellum from the overlying brain. These folds demarcate anatomical boundaries within the skull cavity: the forebrain and diencephalon are located above the tentorium, i.e. supratentorially, whereas the hindbrain (pons, cerebellum and medulla) is located below, or infratentorially. The tentorium contains a gap, the tentorial notch, through which the midbrain and blood vessels pass.

Cortical lobes

When the meninges are removed, one can observe the gross (macroscopic) anatomy of the CNS. Anatomically, the cortex is described according to lobes that are named in relation to skull bones. Thus, there are four lobes visible from the outside of the brain: the occipital, temporal, parietal and frontal lobes. The frontal lobe makes up about one-third, the temporal lobe one-quarter, the parietal lobe about one-fifth and the occipital one-eighth of the entire cerebral cortex. In addition, there is one other lobe that cannot be seen from the outside of the brain: the limbic lobe. It comprises the medial portions of the frontal, parietal and temporal lobes, forming a rim around the corpus callosum (a fibre tract that connects the two cortical hemispheres); it accounts for the remaining 10% of the cortex. Another cortical area, the insula, lies buried in the medial wall of the lateral fissure, overlain by parts of the frontal, parietal and temporal lobes; it is functionally associated with the limbic lobe. The lobes are divided into regions that are associated with specific functions (see Table 1.2).

Surface features: sulci and gyri

The surface of the cortex is highly convoluted and is subdivided into fissures (deep grooves), gyri (elevated folds; singular = gyrus) and sulci (singular = sulcus; shallow grooves between folds). The folds massively increase the surface area of the cortex. The longitudinal fissure separates the two cortical hemispheres, and the lateral fissure (of Sylvius) separates the temporal lobe from the parietal and frontal lobes. The central sulcus and the parieto-occipital sulcus define the boundaries of the frontal and parietal, and parietal and occipital, lobes respectively. On the lateral surface of the hemispheres, the boundaries between parietal, occipital and temporal lobes are established by continuing the line of the parieto-occipital sulcus downwards, to the inferior surface of the hemisphere, and the line of the lateral fissure backwards to meet this line (Fig. 1.3B).

The pattern of sulci and gyri is extremely variable, and defining even the major sulci and gyri is not easy. In general, the surface of each lobe can be divided into three gyri by two sulci. The sulci provide landmarks for identifying lobes and functional areas of the brain. The main lobes, gyri and sulci are shown in Figure 1.3. The central sulcus marks the position of two important functional areas: primary somatosensory cortex and primary motor cortex. The latter lies anterior to this sulcus in the precentral gyrus; the former lies posterior in the postcentral gyrus.

On the medial surface (see Figs 1.3C and 1.6), the cingulate sulcus follows approximately the line of the corpus callosum, extending through both the frontal and parietal lobes. Below this sulcus is the cingulate gyrus (functionally associated with the limbic lobe). This sulcus terminates by passing upwards to form a sulcus that continues onto the lateral surface of the hemisphere as the postcentral sulcus. The central sulcus is usually the sulcus immediately anterior to this sulcus (on the lateral surface). The gyrus in between these two sulci is the postcentral gyrus, which contains the primary somatosensory cortex. Anterior to the point where the cingulate sulcus crosses (to the lateral surface of the brain) is the paracentral lobule, which contains the lower limb primary motor and somatosensory cortical function regions. The gyri (lingular and cuneus) either side of the calcarine sulcus in the posterior part of the brain are associated with vision.

On the inferior surface (Fig. 1.3A) of the temporal lobe, the most medial gyrus is the parahippocampal gyrus, which expands at its anterior end to form the bulbous, hook-like uncus. These are evolutionarily old parts of the cerebral cortex and are concerned, in part, with the olfactory (smell) system and with memory. In the orbitofrontal cortex (the part that sits above the orbit in the anterior fossa of the skull) is located the olfactory gyrus (cortex associated with the sense of smell). These structures form part of the limbic system, which is involved in emotional processing and perception.

Also visible from the underneath of the brain are the cerebellum and brainstem, which together form the hindbrain. The cerebellum is the broccoli-like structure that lies above the fourth ventricle at the back of the head and below the occipital cortex (separated by the tentorium cerebellum). It is the largest part of the hindbrain. The function of the cerebellum is coordination of movements. This includes muscle tone, movement range, smoothness and equilibrium. All parts of the cerebellar cortex are similar in morphology. The functions of the cerebellum are considered in more detail in Chapter 9.

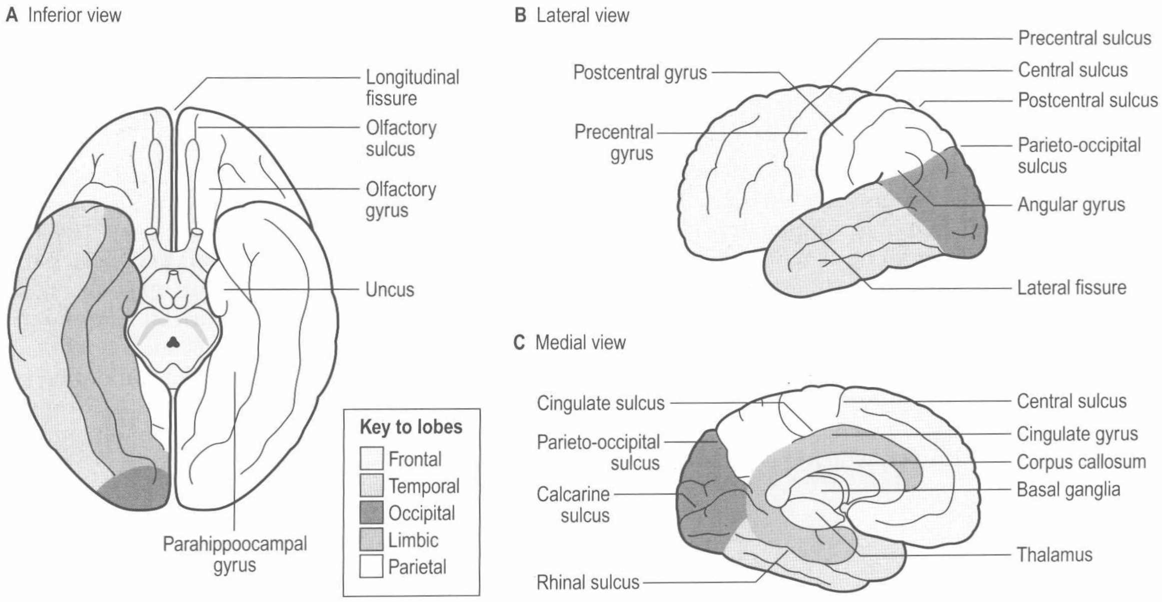


Fig. 1.3

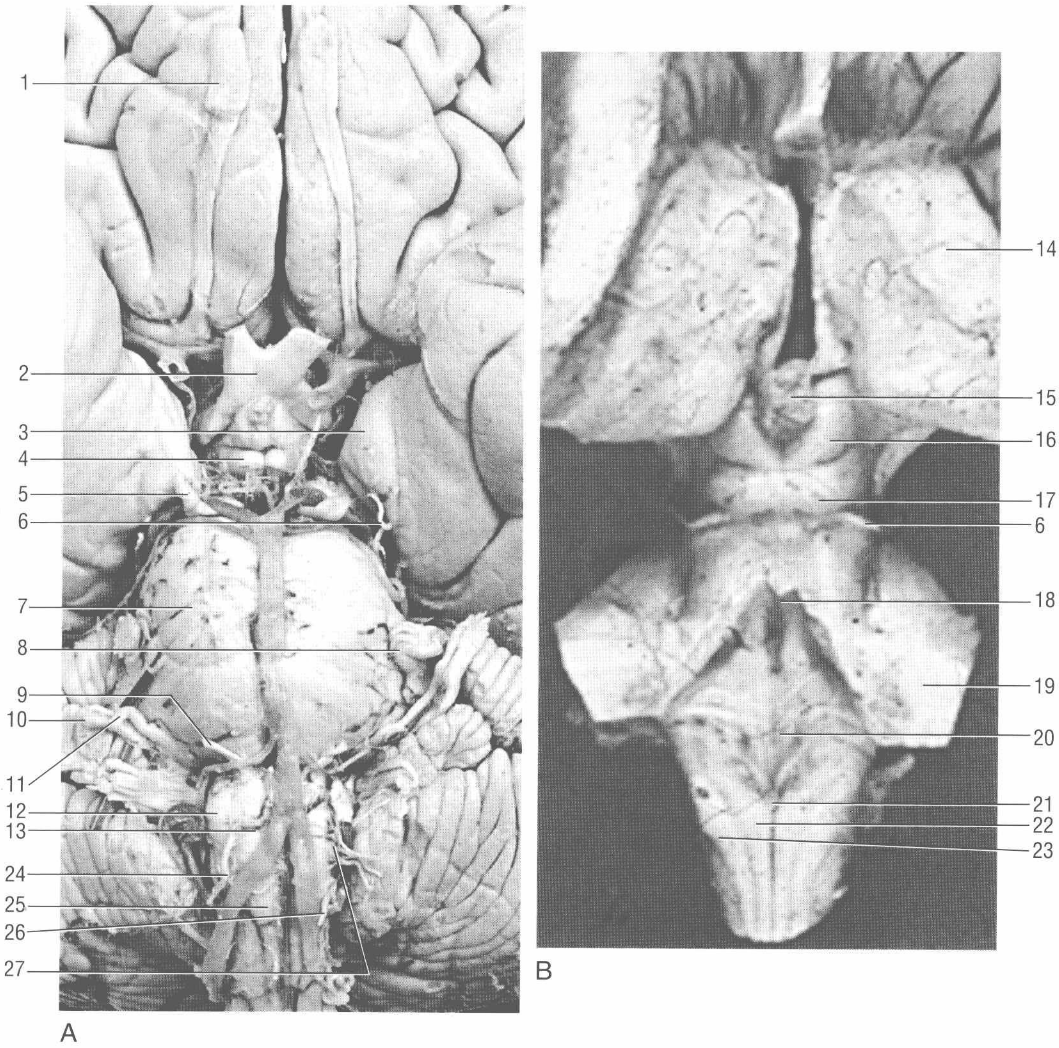
Main gyri, sulci, fissures and lobes of the brain.

Brainstem

The brainstem is located within the posterior fossa of the skull and consists of three parts: midbrain, pons and medulla (Fig. 1.4). These relay information to and from the periphery to higher centres such as the cortex and cerebellum. The brainstem also receives direct input from the cranial nerves. The functions of these nerves and the internal anatomy of the brainstem are described in Chapter 6.

Medulla

On the ventral surface of the medulla are the pyramids. These demarcate the descending motor fibres from the cerebral cortex that give rise to the corticospinal tract



1. CN I.
2. CN II (optic chiasm).
3. Uncus.
4. Mamillary body.
5. CN III.
6. CN IV.
7. Pons.
8. CN V.
9. CN VI.
10. CN VIII.
11. CN VII.
12. Inferior olivary nucleus.
13. Pyramid.
14. Thalamus.
15. Pineal gland.
16. Superior colliculus.
17. Inferior colliculus.
18. Cerebral aqueduct.
19. Middle cerebellar peduncle.
20. Fourth ventricle.
21. Obex.
22. Gracile fasciculus.
23. Cuneate fasciculus.
24. CN XII.
25. Medulla.
26. CN XI.
27. CN IX–X.

Fig. 1.4

Surface anatomy of the brainstem. (A) Ventral view. (B) Dorsal view. CN = cranial nerve.

(CST), also called the pyramidal tracts of the spinal cord. The pyramidal decussation is where most of the CST fibres cross to the other side to become the lateral CST. The decussation marks the location of the spinomedullary junction, i.e. the end of the spinal cord and the beginning of the brainstem. Lateral to the rostral part of the pyramids are two oval swellings that mark the location of the inferior olivary nuclei (ION), which are functionally associated with the cerebellum. They provide a surface landmark for the emergence of cranial nerves IX–XII; nerve XII emerges between the ION and CST, whereas nerves IX–XI emerge laterally to the ION.

On the dorsal surface of the brainstem, the medulla consists of two parts, the open and closed medulla, due to the emergence of the central canal opening into the fourth ventricle. The point at which this occurs is called the obex. The closed part of the medulla shows a pair of gracile and cuneate tubercles that mark the position of the gracile and cuneate nuclei, which transmit sensory information to higher brain centres.

Pons

The ventral pons has a transversely ridged appearance, with a shallow groove running along the midline called the basilar sulcus, which contains the basilar artery. The ridged appearance is due to fibres entering the cerebellum from the nerve cells in the pons, which in turn are the recipients of a major input from the cerebral cortex. The trigeminal nerve is the only nerve to emerge from this ridged region, while cranial nerves VII and VIII exit at the cerebellopontomedullary angle. The position of cranial nerves VI–VIII identifies the pontomedullary junction on the ventral surface.

The pons is sharply demarcated both rostrally and caudally from the other parts of the brainstem. The open medulla and pons together form the floor of the fourth ventricle, which is diamond-shaped. The closure of the rostral part of the fourth ventricle to form the cerebral aqueduct and the cerebral peduncles demarcates the transition from pons to midbrain.

Midbrain

The midbrain is short, and very little of it can be seen in the undissected brain. Ventrally, the cerebral peduncles are located lateral to two small circumscribed mounds, the mamillary bodies (part of the hypothalamus). The peduncles are large bundles of fibres descending from the motor cortex to the brainstem and spinal cord, and comprise chiefly the pyramidal and corticopontine fibre systems. The dorsal surface of the midbrain is called the tectum and has two paired swellings, the inferior and superior colliculi, which are involved in auditory and visual reflexes. These are buried beneath the overlying cerebral hemispheres. Two cranial nerves exit the midbrain, cranial nerve III at the midbrain–pons junction and cranial nerve IV on the dorsal surface.

Spinal cord

The spinal cord connects the brain to the PNS. It is the part of the CNS located outside the skull, below the foramen magnum but within the vertebral column. The spinal level of the nervous system extends from the skull to the sacrum. The spinal cord receives input from the periphery, relays it to the brain and sends response signals back to the periphery. The spinal cord is not segmented; rather, the distribution of the peripheral nerve spinal roots gives it a functional segregation. The details of spinal cord function are described in Chapter 4. The spinal cord consists of grey matter and white matter, like the brain (except that in the spinal cord the white matter is on the outside). The grey matter contains cells and is surrounded by white matter that contains mainly bundles of axons ascending and descending in the spinal cord.

Internal anatomy of the brain

The easiest way to see the various anatomical structures deep inside the brain is to cut it open. However, what is seen depends on the plane of section; the same structures look different in different planes. When the brain is investigated, whether by histology or imaging such as magnetic resonance imaging (MRI), positron emission tomography (PET) or computed tomography (CT) scans, the cross-sections taken in various planes and from various directions are examined (Box 1).

Sagittal sections

If the brain is split in two at the midline, cutting along the sagittal fissure, the cerebrum is divided into its two hemispheres, as shown in Figure 1.6. In this plane, below the corpus callosum we can see most of the deep (subcortical) structures of the brain, the thalamus, the hypothalamus and the ventricular system. Moving laterally in this plane, adjacent sections would also reveal the appearance of the basal ganglia nuclei that are located on top of the thalamus and form part of the lateral walls of the ventricular system. The basal ganglia are more easily viewed in frontal and horizontal sections (see Figs 1.12 and 1.13). In the upper part of Figure 1.6, they are obscured by a thin membranous sheet, the septum pellucidum (which is torn in this specimen). Most of these structures can be seen in the MRI image shown in the lower part of Figure 1.6.

Coronal sections

Frontal (coronal) sections are the easiest plane to visualise, because their orientation is such that viewing them is just like looking at another person face-on. Up is up and down is down. When sectioning from front to back, the very first section seen in a coronal series would be just the tips of the frontal lobes, which are located right behind the forehead. In Figure 1.7, we have moved backwards a little, to the first section containing internal structures. In these sections, the white matter (axons) appears white and the grey matter (cell

Organisation of the nervous system Box 1

Brain topography

Anatomical descriptions of images and tissue sections are based on four anatomical planes, sagittal, horizontal, transverse and median (Fig. 1.5). The horizontal (axial) plane is a plane across the brain that would be horizontal if the patient were standing up. The median plane is one that slices the brain vertically along the midline into two symmetrical halves; sagittal sections are vertical planes through the brain parallel to the median plane. The coronal (frontal) plane is one slicing the brain vertically across (e.g. from ear to ear).

In addition, structures towards the front of the brain are termed anterior (or rostral) and those towards the back are posterior (or caudal). Those towards the top of the brain are termed superior and those towards the bottom are termed inferior. Structures located laterally are further away from the midline, and those located medially are nearer the midline.

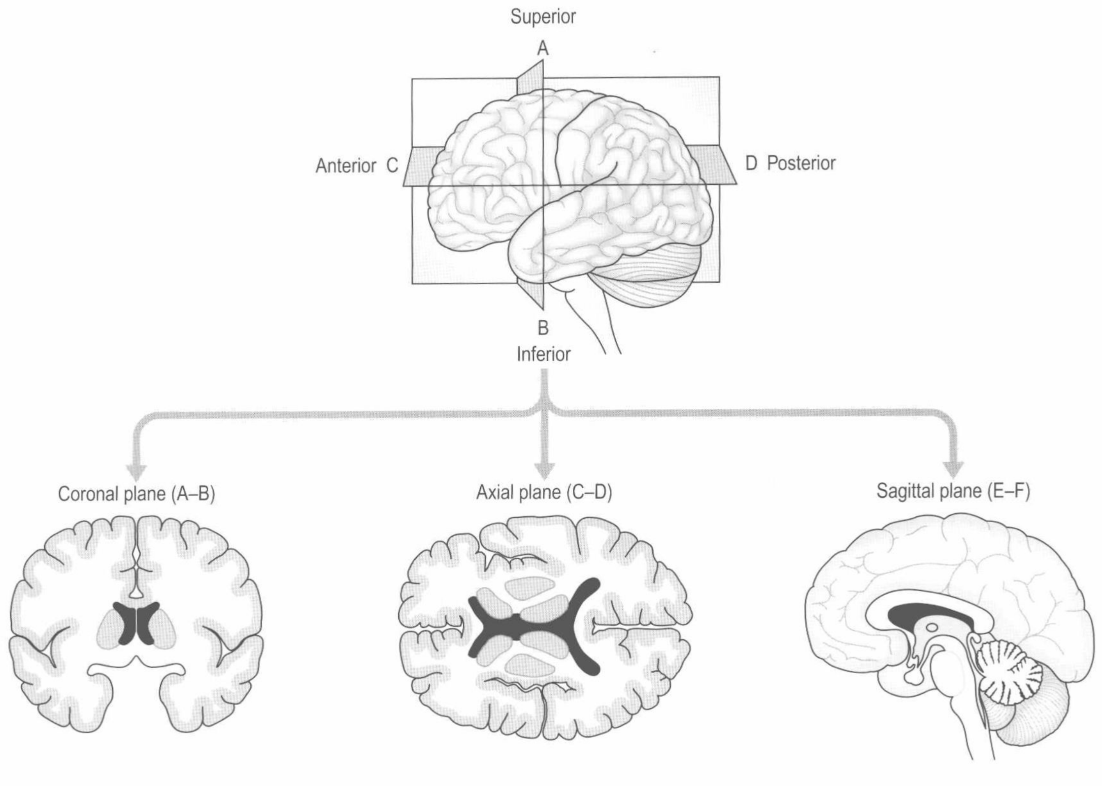


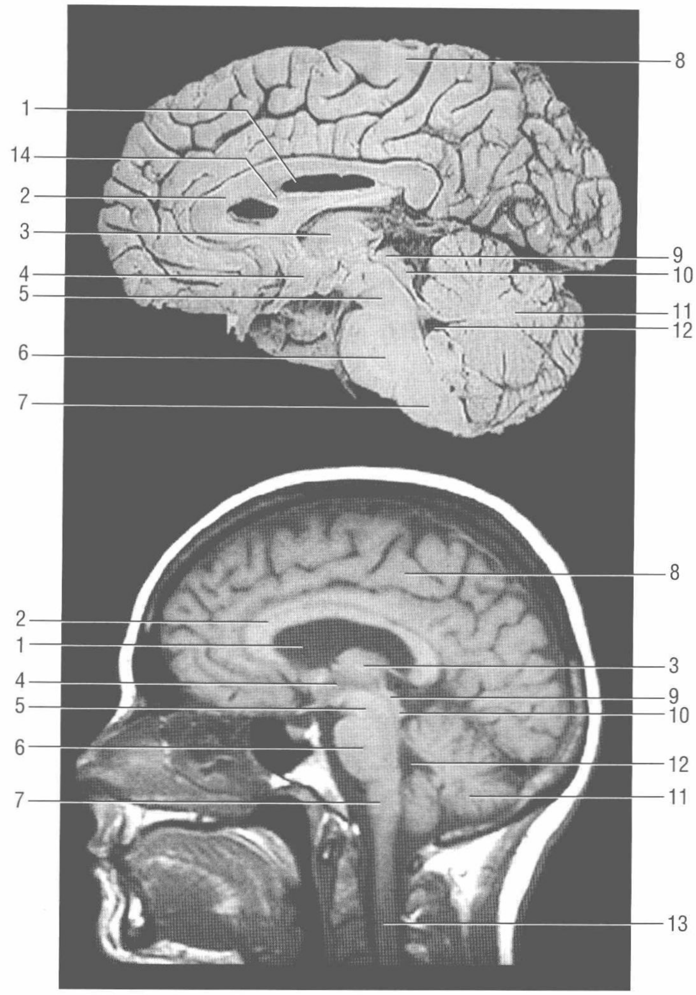
Fig. 1.5

Anatomical planes of section. Shading: black, ventricles; grey, grey matter; yellow, white matter.

bodies) appears grey. The first thing to notice is the corpus callosum. This major pathway connects the two hemispheres and serves as a useful landmark, because it appears in all coronal sections in which deep structures are present.

Below the corpus callosum are the front ends of the two lateral ventricles, separated by the septum pellucidum. The masses of grey matter that form the lateral walls of the lateral ventricles are the caudate nuclei (part of the basal ganglia). The rule for identifying them is simple: if the lateral ventricles are visible, so is the caudate. This applies throughout the curved extent of the lateral ventricles, as the caudate follows them the whole way.

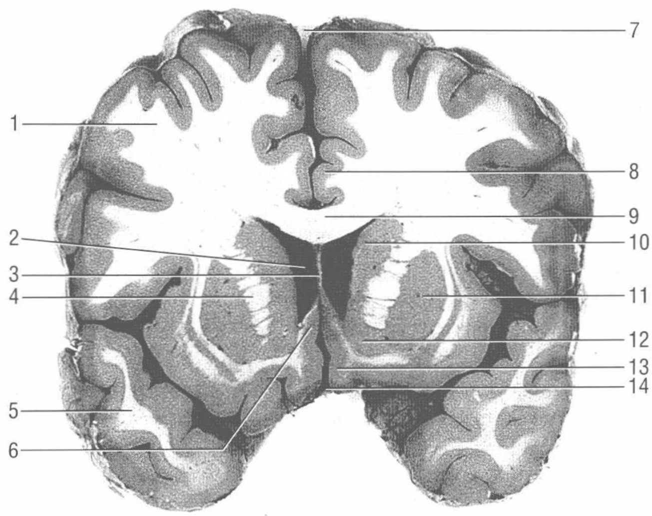
The caudate appears to be joined by threads of grey matter to another nucleus (a nucleus is any collection of cell bodies in the CNS), the putamen. These two nuclei are almost always divided by a band of axons called the internal capsule, which is a major pathway for connections between the thalamus and the cortex. In the rostral brain, these two nuclei are continuous at the base, so that in reality the caudate and the putamen are a single nucleus, divided in half by the internal capsule; hence they are commonly called the striatum. Early anatomists did not realise this, so they were named separately, and the small ventral bridge below the internal capsule which connects them was named the



1. Lateral ventricle.
2. Corpus callosum.
3. Thalamus.
4. Hypothalamus.
5. Midbrain.
6. Pons.
7. Medulla.
8. Paracentral lobule.
9. Superior colliculus.
10. Inferior colliculus.
11. Cerebellum.
12. Fourth ventricle.
13. Spinal cord.
14. Septum pellucidum

Fig. 1.6

Midsagittal section of the brain shown in a gross specimen (top) and at the equivalent level on a magnetic resonance imaging scan (bottom).



1. Frontal lobe.
2. Lateral ventricle.
3. Septum pellucidum.
4. Anterior limb of internal capsule.
5. Temporal lobe.
6. Septal nuclei.
7. Longitudinal fissure.
8. Cingulate gyrus.
9. Corpus callosum.
10. Caudate nucleus.
11. Putamen.
12. Nucleus accumbens.
13. Hypothalamus.
14. Third ventricle.

Fig. 1.7

Coronal section of the brain.

1. Cingulate gyrus.
2. Corpus callosum.
3. Caudate nucleus.
4. Internal capsule.
5. Putamen.
6. Globus pallidus external.
7. Globus pallidus internal.
8. Optic tract.
9. Longitudinal fissure.
10. Lateral ventricle.
11. Fornix.
12. Insula cortex.
13. Lateral fissure.
14. Anterior commissure.
15. Amygdala.
16. Temporal lobe.
17. Hypothalamus.
18. Third ventricle.

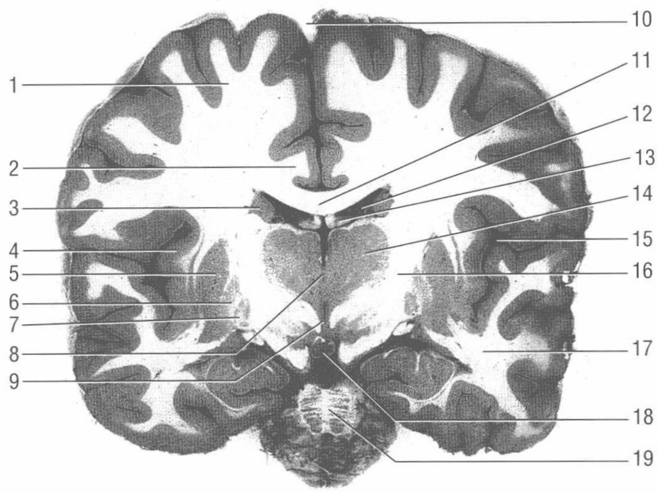
Fig. 1.8

Coronal section of the brain.

nucleus accumbens. The nucleus accumbens and the septal nuclei are associated with conscious 'reward' and motivation and are part of the limbic system. These structures are involved in the mediation of the effects of addictive drugs such as cocaine, heroin and amphetamines.

In the next most caudal section, shown in Figure 1.8, some things have changed. The nucleus accumbens has disappeared and the caudate and putamen are no longer connected. The caudate nucleus is decreased in size, and medial to the putamen there is the emergence of a new set of basal ganglia nuclei. These are the globus pallidus external (GPe) and internal (GPi). We can clearly see the diagonal openings that connect the lateral ventricles with the midline third ventricle. The septum here is very small, and suspended from it like two pieces of fruit are tracts called the fornices (fornix for one tract). The third ventricle is below the fornices. In this section, the left fornix is lower than the right. The fornix connects the mamillary body to the hippocampus (in the temporal lobe). Its inferior part can be seen adjacent to the third ventricle above the hypothalamus. Below the hypothalamus at the base of the brain is the optic tract. Below and between the putamen and GPe and just above the temporal lobe is a white matter tract called the anterior commissure, which connects the temporal lobes of each side. In the medial part of the temporal lobe is a circumscribed region of grey matter, housing the amygdala. The amygdala is a specialised form of cortex, and is part of the limbic system. It deals with the emotional significance of experiences. The insula cortex is also visible at this level. The insula appears to play a role in language and in the integration and perception of sensory stimuli such as pain.

Moving further caudally, in the next section (Fig. 1.9), another major nucleus appears: the thalamus. The thalamus is a heterogeneous group of nuclei that are the gatekeepers for any information passing to and from the cerebral cortex. The thalami are located on either side of the slit-like third ventricle. This provides another anatomical rule: if the third ventricle is visible, so is the thalamus. Sometimes the thalamus will send a little bridge across the third ventricle, appearing to create two smaller ventricles. This is a normal



1. Frontal lobe.
2. Cingulate gyrus.
3. Caudate nucleus.
4. Insula cortex.
5. Putamen.
6. Globus pallidus external.
7. Globus pallidus internal.
8. Interthalamic adhesion.
9. Hypothalamus.
10. Longitudinal fissure.
11. Corpus callosum.
12. Lateral ventricle.
13. Fornix.
14. Thalamus.
15. Lateral fissure.
16. Internal capsule (posterior limb).
17. Temporal lobe.
18. Mamillary bodies.
19. Pons.

Fig. 1.9

Coronal section of the brain.

anatomical variant. The thalamus is located medial to the internal capsule (here the posterior limb), while the putamen and globus pallidus remain lateral to it; this relationship is always preserved and is more easily seen in horizontal sections. The ventral surface of the pons has also been cut, showing the transverse cerebellopontine fibres. The two swellings above it are the mamillary bodies at the base of the midbrain.

In the next section (Fig. 1.10), the globus pallidus and putamen have disappeared. The caudate nuclei are very