Child's Nerv Syst (2002) 18:386–404
DOI 10.1007/s00381-002-0604-1

FOCUS SESSION

María-Trinidad Herrero
Carlos Barcia
Juana Mari Navarro

Functional anatomy of thalamus and basal ganglia

The pathologies that damage the human brain are rarely restricted to single anatomical structures. Stroke, trauma and particularly degenerative diseases do not respect functional anatomical boundaries. But there is much to be learned from observation of what occurs in humans whose brains are damaged by such insults. [12].

Received: 3 January 2002
Published online: 26 July 2002

Abstract *Thalamus:* The human thalamus is a nuclear complex located in the diencephalon and comprising of four parts (the hypothalamus, the epythalamus, the ventral thalamus, and the dorsal thalamus). The thalamus is a relay centre subserving both sensory and motor mechanisms. Thalamic nuclei (50–60 nuclei) project to one or a few well-defined cortical areas. Multiple cortical areas receive afferents from a single thalamic nucleus and send back information to different thalamic nuclei. The corticofugal projection provides positive feedback to the "correct" input, while at the same time suppressing irrelevant information. Topographical organisation of the thalamic afferents and efferents is contralateral, and the lateralisation of the thalamic functions affects both sensory and motoric aspects. Symptoms of lesions located in the thalamus are closely related to the function of the areas involved. An infarction or haemorrhage thalamic lesion can develop somatosensory disturbances and/or central pain in the opposite hemibody, analgesic or purely algesic thalamic syndrome characterised by contralateral anaesthesia (or hypaesthesia), contralateral weakness, ataxia and, often, persistent spontaneous pain. *Basal ganglia:* Basal ganglia form a major centre in the complex extrapyramidal motor system, as opposed to the pyramidal motor system (corticobulbar and corticospinal pathways). Basal ganglia are involved in many neuronal pathways having emotional, motivational, associative and cognitive functions as well. The striatum (caudate nucleus, putamen and nucleus accumbens) receive inputs from all cortical areas and, throughout the thalamus, project principally to frontal lobe areas (prefrontal, premotor and supplementary motor areas) which are concerned with motor planning. These circuits: (i) have an important regulatory influence on cortex, providing information for both automatic and voluntary motor responses to the pyramidal system; (ii) play a role in predicting future events, reinforcing wanted behaviour and suppressing unwanted behaviour, and (iii) are involved in shifting attentional sets and in both high-order processes of movement initiation and spatial working memory. Basal ganglia-thalamo-cortical circuits maintain somatotopic organisation of movement-related neurons throughout the circuit. These circuits reveal functional subdivisions of the oculomotor, prefrontal and cingulate circuits, which play an important role in attention, learning and potentiating behaviour-guiding rules. Involvement of the basal ganglia is related to involuntary and stereotyped movements or paucity of movements without involvement of voluntary motor functions, as in Parkinson's disease, Wilson's disease, progressive supranuclear palsy or Huntington's disease. The symptoms differ with the location of the lesion. The commonest disturbances in basal ganglia lesions are abulia (apathy with loss of initiative and of spontaneous thought and emotional responses) and dystonia, which become manifest as behavioural and motor disturbances, respectively.

Keywords Thalamus · Basal ganglia · Anatomy · Behavioural disorders · Motor disorders

M.-T. Herrero (✉) · C. Barcia
J.M. Navarro
Experimental Neurology
and Neurosurgery Group,
Department of Morphological Sciences
and Psychobiology,
School of Medicine, University of Murcia,
Campus Espinardo, 30071 Murcia, Spain
e-mail: mtherrer@um.es
Tel.: +34-968-364683/3953
Fax: +34-968-363955/4150

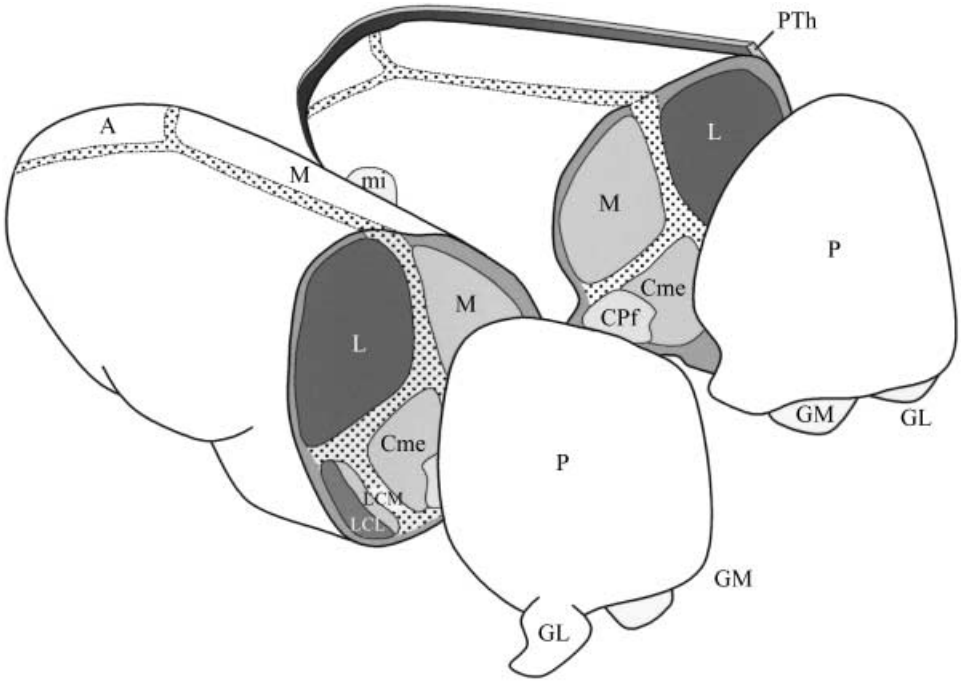

Fig. 1 Diagrammatic view of the internal structure of the dorsal thalamus. The figure represents a posterior view of right and left sectioned thalamus. Note the *regio centralis* of the allothalamus and their organization. The internal medullary lamina separates the regio superior, regio lateralis and regio medialis. Nucleus perithalamicus covers the thalamus (*A* regio superior, *Cme* nucleus centralis medius, *CPf* nucleus centralis parafascicularis, *GL* nucleus geniculatus lateralis, *GM* nucleus geniculatus medialis, *dotted areas* internal medullary lamina, *LCL* nucleus ventralis caudalis lateralis, *LCM* nucleus ventralis caudalis medialis, *L* regio lateralis, *M* regio medialis, *mi* massa intermedia, *P* regio posterior, *PTh* nucleus perithalamicus)

The thalamus

The thalamus is a nuclear complex situated in the diencephalon. The diencephalon forms the central core of the brain and is surrounded by the hemisphere, so that only the basal surface is exposed to external view in a diamond-shaped area containing hypothalamic structures. The diencephalon is located at the dorsal end of the brain stem surrounded by the internal capsule laterally and the lateral ventricles and corpus callosum superiorly. It is divided into symmetrical halves separated by the narrow third ventricle but connected by the massa intermedia (Fig. 1). The rostrocaudal dimension of the human thalamus is about 30 mm, its height about 20 mm and its width about 20 mm. It has been estimated that there are about 10 million thalamic neurons in each hemisphere. The human thalamus is divided into 50–60 nuclei (Fig. 1, Table 1). The names of most of these nuclei are derived from their geographical locations within the thalamus. The thalamus is made up of four parts: the hypothalamus, the epithalamus, the ventral thalamus, and the dorsal thalamus. The traditional partition of the diencephalon into large ontogenic-embryologic subdivisions corresponds to Herricks's columnar model. The new neuromeric model places the hypothalamus in a different neuromere [159]. The epithalamus belongs to the same prosomere as the dorsal thalamus, but we can consider it separately; it comprises the paraventricular complex, the habenular complex and the pretectal group. Moreover, the perithalamus (ventral thalamus) originates from a different prosomere and corresponds to the reticular nucleus, the zona incerta and the pregeniculate nucleus. The dorsal thalamus is in fact the main part of the thalamus.

The dorsal thalamus has two regions:[1] the allothalamic region and the isothalamic region.

The allothalamic region can be divided into:

1. The paraventricular region or midline nuclei (including the massa intermedia) (receiving afferents from the amygdala)
2. The centre-median-parafascicular complex (isolated by a continuous capsule), which appears to be a major element in the basal ganglia system [51, 153]
3. The intralaminar region, which includes the nuclei within the lamina medialis

The isothalamic region constitutes the bulk of the thalamus. It has "bushy" neurons and "microneurons", and most of its connections are directed to the cortical areas receiving an important mass of corticothalamic axons (in primates, much more important than the thalamocortical

[1] Traditionally, (i) a thalamic region is defined as a gross topographical division corresponding to the former nuclei; (ii) a territory such as the cerebral space filled by afferent endings from one source; (iii) the thalamic space where neurons project to a given cortical target constitutes a "source space"; and (iv) a thalamic nucleus is defined as the intersection of a thalamocortical space with one territory. The principal terms in the nomenclature are the 'anteroposterior', 'mediolateral' and 'dorsoventral' subdivisions, but there are three classes of thalamic nuclei in relation to its function: specific, nonspecific and association nuclei (even if the classic concept of nonspecific thalamus has important intranuclear variations [154])

Table 1 Diencephalic elements in hierarchical order (from [154] with permission of the authors). *Situs* are topographic locations. They may or may not correspond to cytoarchitectonic subdivisions

I. Diencephalic nonthalamic elements			
I.A. Perithalamus PTh (ventral thalamus, thalamus ventralis)			
Nucleus perithalamicus		PTh	
	Situs perithalamicus	PTh	(= N. reticularis R)
	Situs incertus	PTh ZI	(= Zona incerta Zi)
	Situs pregeniculatus	PTh Pr	(= N. pregeniculatus or prepeduncularis)
I.B. Epithalamus Hb = habenula			
Nucleus habenulae lateralis	HbL (Hlmc)		
Nucleus habenulae medialis	HbM (Hlpc)		
II. Thalamus T (dorsal thalamus)			
II.A. Allothalamus (neuronal types different from those of the isothalamus)			
i. Regio paraventricularis		E or paramediana	= Midline nuclei + adhesio interthalamica (massa intermedia)
ii. Regio centralis		C	= Centre median–parafascicular complex (basal ganglia)
Nucleus centralis parafascicularis			CPf
Nucleus centralis medius			Cme pallidal thalamus
Nucleus centralis paralateralis			CpL
iii. Regio intralaminaris		Il	= Intralaminar nuclei (in true sense of term)
Nucleus intralaminaris oralis			IlO = paracentralis PCn
Nucleus intralaminaris caudalis			IlC = centralis lateralis CL
Nucleus intralaminaris posterior			IlP = I.La Post
iv. Nucleus limitans		Li	
II.B. Isothalamus (made up of bushy thalamocortical projection neurons + microneurons)			
II.B.1. Regio superior S			
Nucleus anterior	A		Nucleus anterior principalis AV + AM
Nucleus anterodorsalis	AD		Nucleus anterior accessorius
Nucleus superficialis	S		Nucleus lateralis dorsalis
II.B.2. Superregio medioposterior			
i. Regio medialis	M		Main part of the dorsomedial nucleus
Nucleus medialis (man)		M	
Nucleus medialis medialis			MM (amygdalar afferences)
Nucleus medialis lateralis			ML
ii. Regio posterior		P	Main part of the pulvinar
	Nucleus posterior	P4	
	Situs medialis		PuM
	Situs lateralis		PuL
	Situs oralis		PuO
	Situs oralis dorsalis		PuOD (nucleus lateralis posterior)
II.B.3. Superregio basalis			
i. Regio basalis		B	
	Nucleus supragenicularis		Spinothalamic thalamus
ii. Regio intergeniculata		Ig	
	Nucleus intergeniculatus		Tectal thalamus
II.B.4. Superregio inferolateralis (sensory and motor thalamus)			
i. Regio geniculata		G	
	Nucleus geniculatus medialis		GM auditory thalamus
	Nucleus geniculatus lateralis		GL visual thalamus

Table 1 (continued)

Ii. Regio lateralis	L (lateral mass plus paralaminar parts of the dorsomedial nucleus with ventral afferences)	
a. Subregio arcuata		LArc gustatory thalamus
Nucleus lateralis arcuatus		LAc
Sensorimotor thalamus		
b1. Subregio caudalis		LC lemniscal thalamus
Nucleus ventralis caudalis lateralis		LCL
Nucleus ventralis caudalis medialis		LCM
b2. Motor thalamus		
I. Subregio intermedia		LI cerebellar thalamus
Nucleus lateralis intermedius lateralis		LIL
Nucleus lateralis intermedius mediodorsalis		LIM (VIM + DI)
Situs ventralis medialis		LIMm
Situs dorsalis		LlMd
Situs postremus		LlMps
Situs paralaminaris intermedius		plI
II. Subregio oralis		LO pallidal thalamus
Nucleus lateralis oralis		LO (VOL + DO)
Situs principalis		LO1 (VOL = Voe = Vlo)
Situs dorsalis		LOd (DO = Doe = dorsolateral VA)
Situs ventralis		Lov (VOV = VLm, lat)
III. Subregio dorsalis		LR nigral thalamus
Nucleus lateralis rostralis		LR (VOM + LPo)
Situs polaris		Lrpo
Situs perifascicularis		LRmc
Situs ventralis medialis		LRvm
Situs paralaminaris rostralis		PlO
Nucleus lateralis rostralis pars medialis		LRM nigral + amygdalar

projection [154]). The internal and superior laminae divide the isothalamus into several subregions. The internal medullary lamina divides the principal thalamic nuclei into two major parts: a medial group on one side and a ventrolateral group on the other side of the internal medullary lamina (Fig. 1). The anterior part of the internal medullary lamina splits into two lamellae, which surround the anterior group o-nuclei. The cell groups within the internal medullary lamina in the caudal part are the named intralaminar nuclei (allothalamic region) [87].

Since the beginning of the twentieth century, the human thalamus has been divided into subnuclei and in some functional aspects on the basis of anatomical criteria and clinicopathological observations [38, 39, 76, 81, 86]. However, the functional parcellation of the thalamus has suffered from historical and technical drawbacks because of “an archaic, rigid conception of the thalamic nucleus; overexploitation of cytoarchitecture technique, comparative anatomy and cortical connections; underexploitation of subcortical afferent territories, and opposition between ventral (relay) and dorsal (associative) nuclei” [154]. The thalamus is a relay centre in subserving both sensory and motor mechanisms and then, awareness [179], attention [20] and other neurocognitive processes such as memory and language [47, 85]. Thalamic relay neurons receive excitatory glutamatergic input from peripheral sensory pathways [15]. After neuroanatomical tracing studies in primates using stereotactic atlases [140, 198] we know that most of the thalamic nuclei project to one or few well-defined cortical areas, with the exceptions of the reticular nucleus and the intralaminar nuclei, which project diffusely to many areas of the cortex and have been defined as “nonspecific” thalamic nuclei (Fig. 2) [81, 86, 87, 154]. The centromedian and parafascicular nuclei (nucleus centralis medius and nucleus centralis parafascicularis, respectively) also project back to the striatum [153]. Moreover, thalamocortical interconnections may not be simple one-to-one connections between single thalamic nuclei and single cortical areas [81, 154]: multiple cortical areas receive afferents from a single thalamic nuclei and send information back to different thalamic nuclei [63].

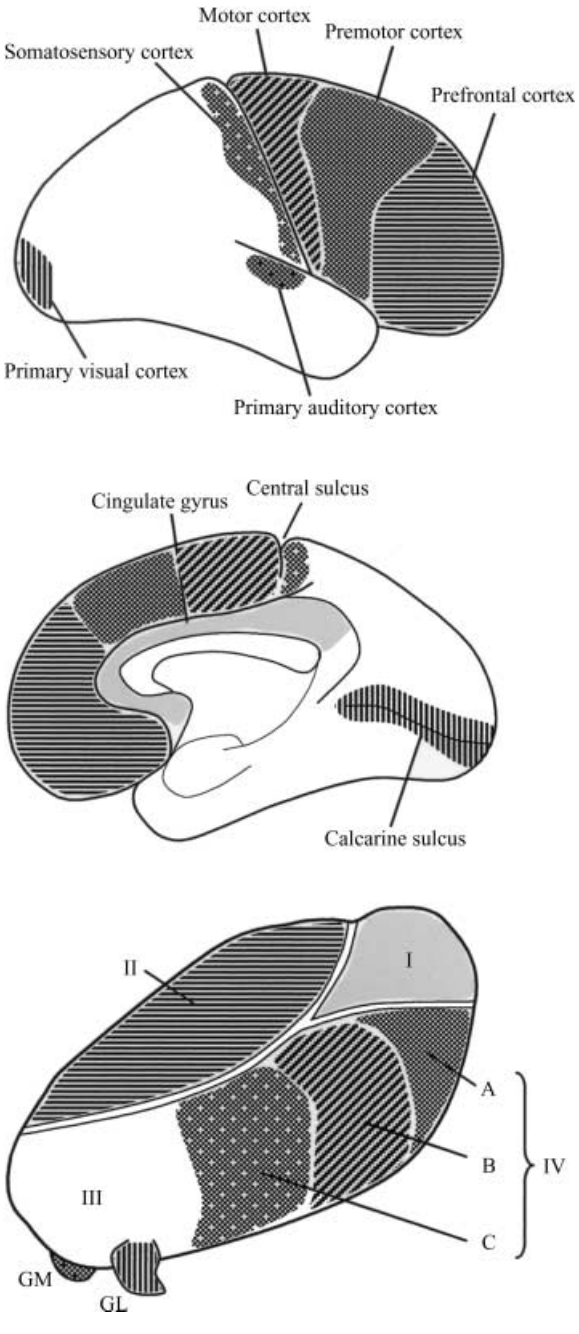

Fig. 2 Distribution of the reciprocal right thalamocortical pathway. *Above*: lateral (*left*) and medial (*right*) surfaces of the hemisphere show the main thalamocortical projections. Correspondences with thalamic nuclei are shown with the same pattern (*below*). [*I* Regio superior (nucleus anterior), *II* regio medialis (nucleus medialis), *III* regio posterior (nucleus posterior), *IV* regio lateralis: *A* subregio oralis + subregio dorsalis (pallidal + nigral thalamus), *B* subregio intermedia (cerebellar thalamus), *C* subregio arcuata + subregio caudalis (gustatory + lemniscal thalamus), *GL* nucleus geniculatus lateralis, *GM* nucleus geniculatus medialis]

In addition to this, the corticofugal projection provides positive feedback to the "correct" input, while at the same time suppressing irrelevant information: a given thalamic neuron receives excitation from a small cortical area that shares the same stimulus selectivity ("egocentric selection") [203]. The corticothalamocortical loops amplify the cortical oscillations (fast synchronous rhythms) [115], but thalamocortical neurons control the slow oscillations [116]. Within the thalamus exist powerful mechanisms that lead the promotion of synchronous and phasic 3 Hz neuronal activity that appears to arise from a perturbation of a physiological higher frequency spindle oscillation [80]. In normal circumstances inhibitory synaptic responses, including those from the reticular nucleus, are required for network synchronisation. Cortical oscillations (fast synchronous rhythms) [115] are differentially affected by lesions of the corticothalamocortical loops and/or by lesions of the different areas involved. Both fast [180] and slow oscillations [116] are synchronised not only in intracortical but also in intrathalamic and thalamocortical networks. Moreover, the role of thalamus in cortico-cortical communication addresses the implications on higher cortical functions when thalamic or corticothalamocortical pathways are involved [63].

The topographical organisation of the afferents at the level of the thalamic nuclei is contralateral. The lateralisation of the thalamic functions affects motoric aspects of different patterns such as speech production and nonverbal memory [85]; however, some nuclei have both contralateral and ipsilateral connections [144]. Instead of this, deafferentation results in reorganisation of the somatosensory map but with different patterns and degrees of somatotopic organisation, all of which may be associated with pain syndromes [88, 92]. The plasticity and reorganisation are mediated by corticofugal loops [49], and it has been suggested that thalamic maps are constantly adjusted by sensory experience [200]. However, the intrathalamic connections [32] are still essential to understand, for instance, how thalamic syndrome produces alterations to visual orientation when somatosensory fields are involved [7].

Each anatomically defined thalamic nucleus has its own characteristic afferent and efferent connections [154]: this defines its function. Two distinct types of thalamic nucleus are proposed on the basis of their afferent fibres from ascending pathways and/or from the cerebral cortex:

1. First-order nuclei, with a modulatory function, receive primary afferent fibres from ascending pathways and receive corticothalamic afferents from cortical layer 6, which sends branches to the reticular nucleus
2. Higher order nuclei receive primary afferents from pyramidal neurons of the cortical layer 5 lacking a branch to the reticular nucleus; its function is concerned with transmitting information about the output of one corti-

cal area to another cortical area (playing a part in cortico-cortical connections on higher cortical functions) [63]; but again, intrathalamic interactions among dorsal thalamic nuclei can also be important [32]

Few neurological diseases have been correlated with changes in a particular thalamic nucleus. The most frequent pathologies are vascular lesions and tumours. Haemorrhagic stroke frequently involves multiple structures in basal ganglia-thalamocortical circuits and, surprisingly, those permit enhanced recovery compared with stroke restricted to the putamen or thalamus [124]. Lesions confined to the thalamus have been associated with asterixis [103], and lesions of the thalamus plus basal ganglia seem to be related to dystonia [104]. Focal lesions of the thalamus and/or of the subthalamic region lead to the development of dyskinesia and bilateral blepharospasm (associated with right posterior thalamic lesions). A classic thalamic syndrome is characterised by contralateral anaesthesia (or hypaesthesia), contralateral weakness, ataxia and, often, persistent spontaneous pain that can be treated by stereotactic thalamotomy [139]. The vascularisation of the thalamus is of a great importance when tumor pathology or infarction is affecting these structures [150]; there is even a correspondence between specific arteries and thalamic areas, which determines the semeiology of thalamic syndromes [18, 47, 133, 188]. A thalamic lesion caused by infarction or haemorrhage can quickly lead to the development of somatosensory disturbances and/or central pain in the opposite hemibody, analgesic thalamic syndrome or a pure algesic syndrome [44]. CT scanning has shown that a paramedian or an anterolateral thalamic lesion (infarction) causes central pain, but a posterolateral ischaemic thalamic lesion will not be accompanied by central pain [194]. The posterior cerebral artery stroke syndrome involving the lateral thalamus (superregio inferolateralis) includes visual field deficits and, frequently, sensory, slight motor, neuropsychological and unilateral headaches or migraine [18]. When the haemorrhages are restricted to the ventral posterior lateral territories of the thalamus (regio lateralis) this leads to a cheiro-oral syndrome [175] or choreiform and dystonic movements associated with rhythmic, alternating movements of low-frequency (myorhythmia) [108]. When tumours involve the inferolateral nucleus of the thalamus one symptom can be mutism, which is defined as a state in which the patient is conscious but unwilling or unable to speak, even if this is usually a transient condition [34]. On the other hand, if a tumor grows slowly and infiltrates tissue rather than destroying it, symptoms will evolve slowly and may be overlooked for a long time. The two basic mechanisms by which tumours produce symptoms are:

1. Focal disturbances resulting from compression, irritation or destruction of adjacent tissue
2. Elevation of the intracranial pressure and intracranial herniations produced by the oedema and the tumour mass

Tumours located deep in the brain, (involving the central region of thalamus and/or basal ganglia and spreading bilaterally) can produce internal hydrocephalus, corticospinal signs, extrapyramidal symptoms, dementia, and even neuroendocrine dysfunction. The symptoms of lesions located in different parts of the thalamus are closely related to the function of the areas involved (nuclei are named as in Table 1).

Nucleus perithalamicus

The reticular nucleus, which surrounds much of the thalamus like an eggshell, especially on its lateral side, was described by Kölliker [94] as the “Gitterkern” or lattice nucleus, as the fibrous latticework is a characteristic feature of this area. It contains inhibitory GABAergic neurons, which exert weak or strong inhibitory connections with significantly different responses on thalamic neurons [31]. A thalamic nucleus that does not project to the cortex, however, receives collaterals from thalamocortical and corticothalamic axons. It is in an excellent position to monitor the activity in the corticothalamic and thalamocortical channels and to transmit information back to the thalamus and the midbrain. Then the reticular nucleus controls the activity of thalamocortical channels, which is of fundamental importance for the two-way thalamocortical and corticothalamic connections [1, 14]. The reticular nucleus can be divided into sectors that are connected to more than one thalamic nucleus and to more than one cortical area: and each sector has topographically mapped connections with the thalamus and the cortex, and each has a different function (sight, hearing, touch, movement or limbic functions) [64].

Allothalamus

The intralaminar nuclei have been included in the “nonspecific ascending reticular activating system” projecting to extensive areas of the cerebral cortex the inputs received from the brain stem reticular formation [151]. These nuclei have been functionally associated with attention, arousal and consciousness. The nuclei are divided into a rostral group and a central-caudal group. A unique combination of calcium-binding protein staining clearly delineates the intralaminar nuclei. The regio intralaminaris (nucleus intralaminaris oralis or paracentralis, nucleus intralaminaris caudalis or centralis lateralis) showed intense staining for both calretinin and calbindin-D28 k [129]. The central-caudal group (regio centralis: nucleus centralis parafascicularis and nucleus centra-

lis medius) showed a complementary pattern of staining: the nucleus parafascicularis shows immunoreactivity for both calbindin-D28 k and calretinin, while the nucleus centralis medius shows immunoreactivity only for parvalbumin. As the nuclei from the regio centralis have important connections with the basal ganglia [153], it has been suggested that calcium-binding protein may play an important role in the interactions between cerebral cortex and the basal ganglia [129]. By way of nonselective inputs, mainly from the cholinergic brain stem nuclei as pedunculopontine nucleus and laterodorsal nucleus, the central-caudal group could modify the activity of the basal ganglia-thalamocortical loops [62]. In fact, there is a loss of neurons in the caudal intralaminar nuclei in Parkinson's disease and in progressive supranuclear palsy [69]. This central group is prominent in primates: the motor functional importance in the basal ganglia circuitry is related to the nucleus centralis medius, whereas the nucleus centralis parafascicularis is related mainly to cognitive, oculomotor and limbic functions [168]. The functional role of these nuclei remains uncertain. They have been proposed as an appropriate target for the treatment of intractable deep pain of central origin or following stroke or due to cancer, as they receive nondiscriminative or affective sensory information [11]. However, even if the nuclei are projecting diffusely to much wider cortical areas (to one or few well-defined cortical fields) as a part of the "diffuse" or "nonspecific" ascending activating system its nonspecificity has been questioned [62, 117].

Isothalamus

Regio superior

The nucleus anterior receives projections from the mammillary body (mammillothalamic tract) and projects to the cingulate cortex belonging to the Papez circuit, the neural circuit for emotion [75, 143]. Lesions involving the nucleus anterior resulted in neuropsychological dysfunction (aphasia and memory impairments) [133, 136] and in anomia for proper names [125]. Then, cognition, memory and emotion affect each other reciprocally, and atrophy or dysfunction of the midline groups has been associated with anterograde amnesia [148, 192]. Tumours involving part of the Papez circuit, such as the anterior nucleus of the thalamus, the hypothalamus and even the anterior part of basal ganglia, disclosed memory disturbances (but not emotional impairment), and after surgery of the tumour an improvement in memory function has been reported even though radiation therapy can decrease the intellectual ability [136].

Superregio medioposterior

Regio medialis. The nucleus medialis receives a large projection from the rhinal and dorsolateral prefrontal cortices [149], amygdala, ventral globus pallidus and nigral projections [27, 164, 169]. It projects to the orbital, medial and dorsal prefrontal cortex [141, 163] and shows strong degeneration after frontal leucotomy [142]. The nucleus shows an intensive pattern of cannabinoid receptors, as many of the regions are associated with higher functions [60]. It has been implicated in cognition [9], recognition memory [136] and habituation, in olfaction [157], in the wake–sleep cycle, in respiration [3] and in other vegetative and endocrine circadian activities [10]. In the case of infarcts involving the anterior or medial region of the thalamus (both regio superior–regio medialis), a loss of memory processes and cognition disorders have been described in the acute phase of insult [89]. Moreover, it may be important to look at the consequences of thalamic infarctions, the damage to the nucleus medialis and nuclei of the allothalamus, or a combined lesion of these structures for deficits of executive functioning [188]. After a bithalamic infarction involving the nucleus medialis a syndrome of lost physical self-activation is common; this includes apathy, indifference and poor motivation [48].

Regio posterior. The pulvinar-lateral posterior complex, which has reciprocal connections with the associated parieto-occipito-temporal cortical areas, is involved in visual and language functions. The pulvinar has a role in selective visual attention. It has four areas (medial, central, lateral and lateral shell) demarcated by acetylcholinesterase and cytochrome oxidase [28]. Even if its lesions are apparently silent they can affect superior functions involving visual and language modalities and are related to hallucination experiences in patients.

Superregio basalis

Regio basalis. The *nucleus suprageniculatus* is located posteromedial to the nucleus ventralis caudalis lateralis (lemniscal thalamus), ventral to the regio posterior (pulvinar) and the regio ventralis (allothalamus), lateral to the nucleus centralis parafascicularis and dorsal to the nucleus geniculatus medialis. The nucleus is the relay for pain and temperature sensation [33], including visceral information [24, 54]. Pain is a message that is protective in nature. There are two pain systems, one signalling the discriminative aspects of pain (location and intensity) and the other, the affective aspects of pain. Our response to a noxious stimulus reflects the actions of both systems [196]. The spinothalamic tract arises from cells in lamina I and lamina V of the dorsal horn and projects to the nucleus suprageniculatus of the thalamus [161] establishing

simple axodendritic synapses [162]. The calbindin-immnunoreactive fibres belong to the lamina I spinothalamic tract fibres and to the vagal-solitary-parabrachial afferents, representing different aspects of enteroceptive information and regarding the physiological status of the tissues and organs of the body [16]. In humans, vascular infarcts in this region cause analgesia and thermoanaesthesia and can lead to the paradoxical development of central pain. It has even been suggested that activation of thermal pathways may contribute to modulation of nociceptive information [46]. The thalamic pain syndrome has been studied and located by anatomical (magnetic resonance imaging) and metabolic correlation in the same area [44]. The nucleus evokes painful and nonpainful paraesthetic cutaneous sensations when stimulated. The pain is described as "like having a baby", and the stimulation of a ventrocaudal region to the ventrocaudal nucleus evokes visceral pain and even triggers pain memories [36, 37]. Moreover, the dorsal aspect of this nucleus has a significant tonic, graded response to cool stimuli and to innocuous mechanical stimuli [106].

Superregio inferolateralis

Regio geniculata. The *GM (nucleus geniculatus medialis)* is situated lateral to the midbrain tegmentum in the caudal region of the diencephalon rostral to the pulvinar. It has three parts:

1. A medial part with magnocellular neurons which receive somatosensory, vestibular and auditory afferents.
2. A dorsal part, a small nucleus, receiving visual and auditory inputs.
3. A ventral part with parvocellular neurons which receive only auditory signals.

The brachium from the inferior colliculus enters the nucleus in its posteromedial aspect. The acoustic radiation begins in the anterolateral border of the nucleus and curve in an anterior direction through the white matter within the transverse temporal gyrus to reach the primary auditory cortex. Clinically, it has been reported that a small haemorrhagic infarction located in the nucleus has caused auditory illusions, such as hyperacousia and palinacousia [57], dichotic listening and complete extinction of the contralateral ear input [53]. Lesions, such as bilateral putaminal haemorrhage, involving the acoustic radiation cause auditory agnosia for all sounds or for environmental sounds only [185].

The *GL (nucleus geniculatus lateralis)* resembles a hat in shape and is positioned inferior to the pulvinar and lateral to the nucleus geniculatus medialis. In sagittal MR images the nucleus lies anterior and superior to the hippocampal formation and in coronal MR images the nucleus is situated between the pulvinar and the cerebral crus (the corticospinal fibres in the anterior part of the midbrain). Microscopically, it is made up of six layers separated by thin white layers. The retinotopy is easily studied by functional magnetic resonance imaging [26]. The optic radiation begins in the posterior half of the lateral side of the nucleus and curves over the temporal horn of the lateral ventricle to reach the primary visual cortex [25]. Both the nucleus and the optic radiation can be analysed by MRI for the interpretation of the brain lesions [21]. Lesions involving the nucleus or the optic radiation may result in homonymous quadrantanopia and homonymous hemianopia. The syndrome of posterior choroidal artery territory infarction includes homonymous quadrantanopsia, neuropsychological dysfunction (aphasia and memory disturbances) with or without hemisensory loss, and the damage involves the nucleus geniculatus lateralis, the posterior thalamus, the nucleus anterior and other regions, such as the hippocampus or the parahippocampal gyrus [133].

Regio lateralis. Subregio arcuata. The *gustatory thalamus*, just rostral to the lemniscal thalamus, is the relay for gustatory sensation receiving the inputs from the rostral part of the lemniscus medialis (trigeminal pathway). The posterior border of the ventral posterolateral nucleus (nucleus ventralis caudalis lateralis) leading to the pulvinar is indicated by a triangular area (Wernicke's triangular area), and patients with lesions of this region demarcated by the posterior limb of the internal capsule, have an absence of sensitivity.

The nucleus of the subregio caudalis lemniscal thalamus is found lateral to the internal medullary lamina, caudal to the ventral intermediate nucleus (subregio intermedia) and rostral to the pulvinar. Laterally it is surrounded by the nucleus reticularis (nucleus perithalamicus) and the external medullary lamina, and dorsally by the nucleus posterior. The lemniscus medialis enters this thalamic nucleus on its inferomedial aspect at its border with the pulvinar. The nucleus has a role as a somatosensory information modulator [127]. A three-link neuronal chain forms the lemniscus medialis system, connecting the mechanosensory and propioceptive receptors neurons of the extremities, trunk, neck and back of the head with the primary somatosensory cortex throughout the thalamus using glutamate as a transmitter [40]. However, a visceral nociceptive input to this nucleus has also been described [4]. It has been reported that single ischaemic lesions in the nucleus lead to development of the sensory thalamic syndrome [175] whose basic symptom is chronic pain [199]. Moreover, as sensory inputs have a significant role in dystonia, a reorganisation in the cutaneous receptive fields at the level of the lemniscal thalamus has been described in dystonia [105].

The *motor thalamus* can be identified as the nuclei that transfer information from the substantia nigra (sub-

regio dorsalis), the globus pallidus (subregio oralis) and the cerebellum (subregio intermedia) to the prefrontal, supplementary, premotor, motor and somatosensory areas of the cerebral cortex [78, 118, 154]. Notwithstanding these segregated pathways, there are overlapping projections to the pre-supplementary motor area, where there are interdigitating foci of pallidal and cerebellar territories [170]. All the thalamic motor neurons become active before the onset of movement [193]. In the nucleus a "voluntary unit" has been described, a cluster of neurons that are linked to rhythmic activity [160]. These neurons are activated only by voluntary movements of the contralateral limb and not by passive movements [160]. The motor thalamus receives projections from the nucleus perithalamicus in a specific diffuse manner, which can also contribute to the transfer of motor information [82]. One report described how a lesion in the basal territory of the thalamus (ventral anterior and ventral lateral nuclei: subregio dorsalis and subregio oralis) either severely disrupted or completely prevented the relearning of a motor task [23]. Focal lesions involving the posterolateral quadrant of the thalamus are associated with abnormal movements [175]. The cerebellar thalamus connections with motor cortex are an essential component in the pathophysiology of tremor [120]. The nucleus lateralis oralis (LO/VOL) has received much attention in stereotactic treatment of Parkinson's disease and other involuntary motor disorders [135, 184], and thalamotomy of the motor thalamus is effective for dystonia treatment even if the concrete target is not well defined [113]. Thalamotomy of the nucleus lateralis oralis ameliorates rigidity but not tremor [137], but the thalamotomy of the subregio intermedia (LIM/Vim), the cerebellar thalamus, results in a permanent abolition of the tremor without affecting the general somatic sensation [68, 138]. Multiple sclerosis patients with disabling tremor have also benefited from thalamotomy [111]. Moreover, thalamotomy is also recommended for the treatment of dystonia [113], as thalamic activity of this nucleus contributes to dystonic movements [107].

Conclusion

The thalamus has been of great interest as a target organ in stereotactic surgery for pain relief and in treatment of movement disorders [83, 181, 202]. In fact, even as early as the second part of the nineteenth century, the living human thalamus was studied directly by a stereotactic approach and some atlases constructed using the intercommissural line (connecting the anterior and posterior commissures in relation to the third ventricle) [67]. Recently, some changes have been brought about by standardisation procedures correcting the antero-posterior co-ordinates in relation to different intercommissural distances, to interindividual nuclear variations [126] or based on intraoperative neurophysiological data and intraoperative X-ray films [201], or in detailed studies preserving post-mortem anatomical structures [98]. However, it is still far from easy to achieve the desired localisation in functional surgery of the thalamus, because many of the nuclei "remain unstudied enigmas" [186].

The basal ganglia

The term basal ganglia has not been precisely delimited and there is no generally accepted definition. Classic anatomists described the "deep large grey masses" collectively as the basal ganglia of the telencephalon, which are embedded in the white matter of each cerebral hemisphere. Initially 'basal ganglia' was a descriptive term for use in onto-phylogenetic or topographic classifications (even the thalamus was regarded as a part of the basal ganglia until the work of Vicq d'Azyr in 1786). The basal ganglia include the caudate nucleus, the lentiform nucleus (the distinction between the putamen and the pallidum was not made until the beginning of the twentieth century), the subthalamic nucleus and the substantia nigra (Fig. 3). The largest of these structures is the corpus striatum. The corpus striatum (neostriatum), which is especially well developed in man, comprises the caudate nucleus and the putamen. The caudate nucleus assumes the shape of a comet curving along the lateral wall of the lateral ventricle. It consists in a large head at the front, a narrow dorsal body and a thin tail which follows a course passing ventrally along the temporal horn of the ventricle and ending at the amygdaloid body. The inferior part of the head is connected with the putamen at the ventral part, at the level of the nucleus accumbens. The demarcation of the caudate nucleus at the level of the body and tail is easy, as is surrounded medially by the lateral ventricle and laterally by the internal capsule. The head of the caudate nucleus and the putamen are connected by thin bridges of grey matter (pontes grisei caudatolenticularis). The putamen is a shell-shaped structure situated medial to the cortex of the insula and surrounded laterally by the external capsule, medially by the lateral medullary lamina of the globus pallidus, and superiorly by the white matter of the corona radiata. in T1-weighted MR images putamen is demarcated by the white matter and the globus pallidus, which are less signal intense. The globus pallidus (paleostriatum) has two parts, medial and lateral. Both lie medial to the putamen, and together with it, constitute the lentiform nucleus. The lateral medullary lamina separates the lateral globus pallidus from the putamen, and the medial medullary lamina separates the medial from the lateral globus pallidus. Medially it is limited by the posterior limb of the internal capsule, while inferiorly it lies close to the substantia innominata and the anterior commissure in the rostral part. The subthalamic nucleus is a small lentiform

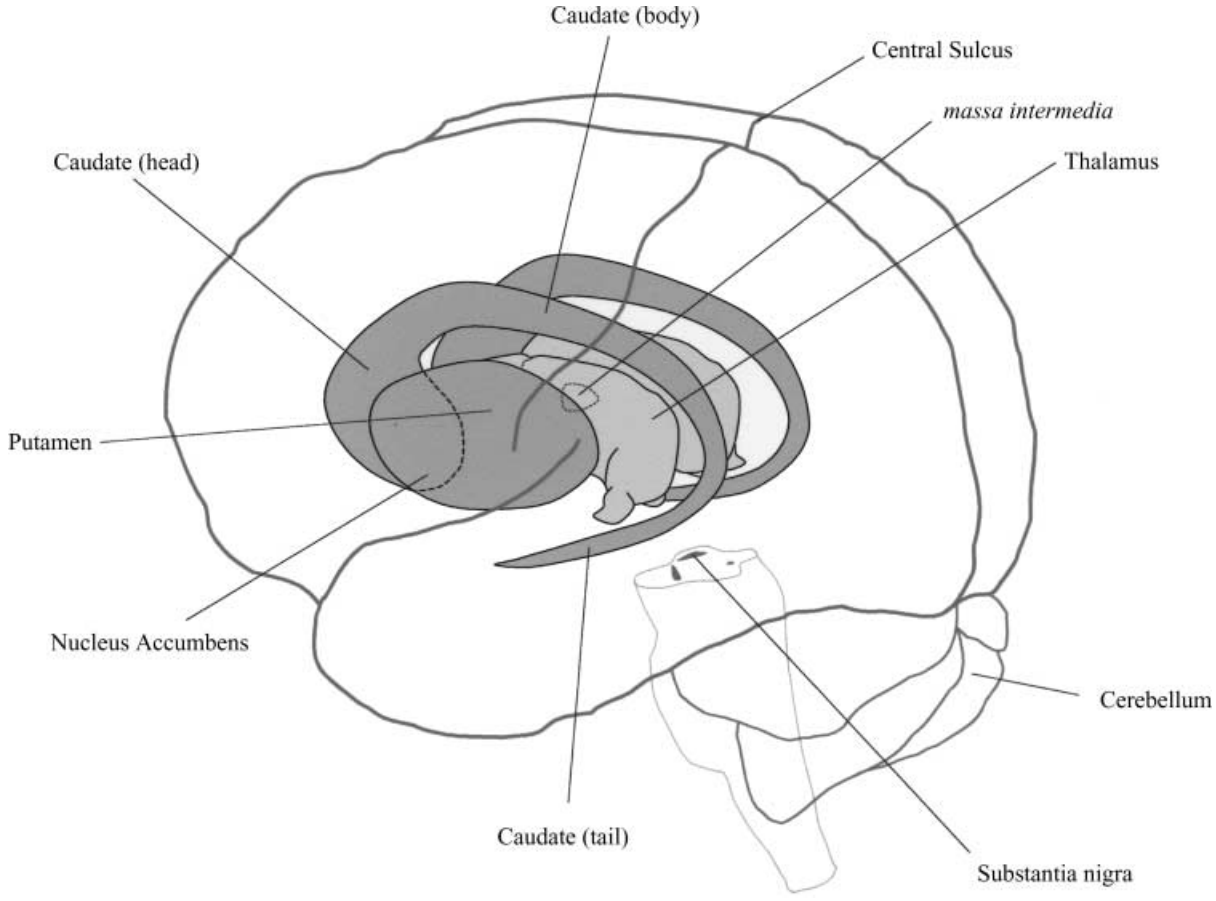

Fig. 3 Anatomical localisation of thalamus and basal ganglia, viewed from the left. Thalamus and basal ganglia are located close together. Lesions do not usually involve one nucleus only, but affect multiple structures in basal ganglia-thalamocortical circuits. Note the massa intermedia connecting right and left thalamus (*discontinuous trace*)

nucleus located at the border between the midbrain and the diencephalon. It is bordered medially by the posterior limb of the internal capsule, dorsally by the lenticular fasciculus and ventrally by the zona incerta. As the subthalamic nucleus is surrounded by white fibres, it is easily demarcated in T1- and T2-weighted MR images. The substantia nigra lies in the ventral tegmentum of the midbrain. The pars compacta is the largest part; it is dorsal and caudal to the pars reticulata. In post-mortem tissue the pars compacta is defined by the black staining by neuromelanin (included in dopaminergic neurons).

The anatomical and functional organisation of the basal ganglia help us to understand how motor and cognitive functions operate in normal and in diseased brain. The basal ganglia make up a major centre in the complex extrapyramidal motor system, as opposed to the pyramidal motor system (corticobulbar and corticospinal pathways). The basal ganglia have been considered a motor centre since the end of the nineteenth century: "the corpus striatum contained the centres of automatic or sub-voluntary integration of the various motor centres where habitual or automatic movements become organised" 52]. Its motor actions are mediated through the pyramidal system [187], as the basal ganglia do not make direct output connections to the spinal cord [152] even if parallel projections from the substantia nigra pars reticulata to the tectum and the reticular formation can descend to the spinal cord (through the tectospinal and reticulospinal pathways). The basal ganglia participate in many neuronal pathways, and their functions are not restricted to the motor behaviour: they also have emotional, motivational, associative and cognitive functions [6, 19, 93, 130, 167, 171, 172]. Moreover, the basal ganglia have a role in error correction mechanisms [102], in which striatum is a central selection device [165]. New concepts have been established by basic research in human and in nonhuman primates [29, 166] and by a practical ex vivo method of learning functional thalamic and basal ganglia anatomy [195].

It was not until the 1960s that the importance of the striato-pallido-nigral network (the "Nauta-Mehler loop") was recognised [132]. The main transmission circuit of the basal ganglia originates in the whole of the neocortex [66, 174] (Fig. 4, left). The caudate and putamen receive

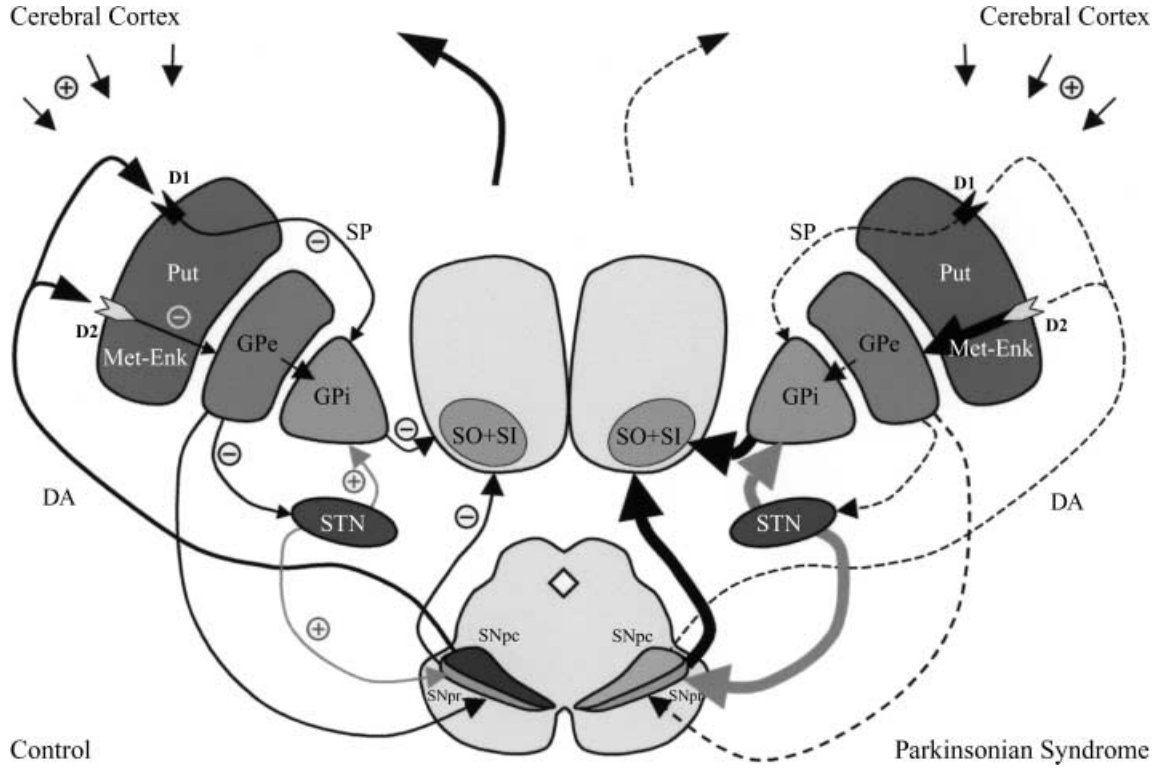

Fig. 4 Cortico-basal ganglia-cortical circuitry (through thalamic nuclei) in control brain (*left*) and in one affected by parkinsonian syndrome (*right*). In the latter, imbalance in both direct and indirect pathways is seen by the size of the *arrows*. Note hyperactivity of output nucleus of basal ganglia circuit (substantia nigra pars reticulata and internal globus pallidus) and subthalamic nucleus in parkinsonian syndrome. Only a subset of basal ganglia pathways is shown (*D1* dopamine receptor type 1, *D2* dopamine receptor type 2, *SP* substance P, *Met-Enk* met-enkephalin, *DA* dopamine, *Gpe* external globus pallidus, *Gpi* internal globus pallidus, *SNpc* substantia nigra pars compacta, *SNpr* substantia nigra pars reticulata, *STN* subthalamic nucleus; *SO* subregio oralis, *SI* subregio intermedia

inputs from associative areas of the neocortex and the sensorimotor cortex (dorsal basal ganglia circuit), and the nucleus accumbens receives input from the orbitofrontal cortex and other limbic cortical areas as well as from the hippocampus and the amygdala (ventral basal ganglia circuit) [58, 131]. Dorsal and ventral basal ganglia circuits are anatomochemically segregated in relation to the relative abundance of parvalbumin striatal interneurons [58, 173] and to the nitric oxide synthase mRNA expression [134]. Both circuits start in the cerebral cortex (and/or subcortical telencephalic structures) throughout the neostriatum, paleostriatum and the ventral thalamic nuclei and reach not only the motor and premotor areas of the frontal lobe concerned with the motor planning but also the associative and limbic cortical areas of the frontal lobe [182]. The funnel system of information flow has been discarded in favour of the five parallel and largely segregated loops pertaining to motor, oculomotor, cognitive, associative and limbic functions related to the major cortical areas of origin, which maintain apparently segregated parallel pathways through the striatum, both segments of the globus pallidus, the subthalamic nucleus and the substantia nigra pars reticulata with a strict somatotopic organisation [5, 6, 19]. However, these five parallel loops are not completely independent; there is a convergence of information:

1. At the level of the globus pallidus and substantia nigra pars reticulata [55, 95, 153]
2. At the level of the thalamus [176]
3. By axonal collateralisation within the different nuclei [147]

It is likely that the parallel but convergent and integrative mechanisms is the reason for the varied symptomatology seen in basal ganglia disease [131].

The efferent neurons of the striatum are the medium spiny neurons which have a common morphology in terms of dendritic organisation, local axon collaterals and size. All of them are GABAergic neurons. However, there is some segregation of projections. The efferences from the striatum are divided into a dual projection of striatal outputs, some neurons projecting to the internal globus pallidus and the substantia nigra pars reticulata (the striatal direct output pathway) and others to the external globus pallidus (the striatal indirect output pathway) (Fig. 4, left) [146]. The direct pathway is provided

by D1-dopamine receptors, substance-P and dynorphin-containing neurons. The indirect pathway is provided by D2-dopamine receptors and enkephalin-containing neurons. Output neurons of the external globus pallidus are GABAergic and exert an inhibitory effect on the subthalamic glutamatergic neurons, which in turn send excitatory projections to both output nuclei of the basal ganglia (namely the internal globus pallidus and the substantia nigra pars reticulata, whose neurons are GABAergic as are those of the external globus pallidus). Both pathways then provide antagonistic effects to the output of the basal ganglia: the direct pathway sends an inhibitory input to both nuclei, whereas the indirect pathway results in excitatory input (Fig. 4, left). The dual projection from the output nuclei of the basal ganglia to the different nuclei of the thalamus (regio lateralis, regio centralis and regio dorsalis; see above) is organised in parallel and somatotopically [5, 55] while, again, thalamic neurons send convergent inputs to the same cortical areas but different laminae [77]. The function of basal ganglia is modulated by both striatal and extrastriatal dopaminergic innervation [30, 177]. However, dopamine in striatal spiny neurons gives rise to synapses at dendritic spines that are also modulated by excitatory inputs from the cortex [178]. In these circumstances, striatal spiny neurons are trained by a dopamine-mediated reinforcement signal to recognise and register salient contexts and/or states that are likely to be useful in guiding behaviour [79].

The pathophysiological changes that occur in disorders of the basal ganglia have been clarified in recent years by experimental approaches using the MPTP (1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine) model of parkinsonism in non-human primates. MPTP is a neurotoxin that induces extensive dopaminergic degeneration resulting in a parkinsonian syndrome [70, 90]. The basal ganglia are organised in such a fashion that nigrostriatal denervation (the hallmark of Parkinson's disease) leads to overactivity of the internal globus pallidus and the substantia nigra pars reticulata (Fig. 4, right) [74, 190]. The pathological hyperactivity of both these nuclei and the subthalamic nucleus [191] has been seen as the result of a reduced inhibitory input from the striatum to the direct pathway [109] and increased activity of the indirect pathway [71]. However, the activity and function of other nuclei, such as the external globus pallidus, needs to be better understood [73], and clinical symptoms of Parkinson's disease or other pathologies, even the symptoms observed by focal pathology, are not fully explained by the current models of basal ganglia circuitry [110, 114].

The study of 240 cases with lesions in the basal ganglia [12] has indicated that the commonest disturbances in basal ganglia lesions are the syndrome of abulia (apathy with loss of initiative and of spontaneous thought and emotional responses) and dystonia, which manifest as behavioural and motor disturbances, respectively. The symptoms differ depending on the location of the lesion: when lesions affect the caudate nucleus even unilateral lesion can cause abulia, or more rarely disinhibited behaviour; and occasionally they cause motor disorders (never cause parkinsonism but sometimes chorea or dystonia); lesions of the lentiform nucleus commonly cause dystonia and rarely cause chorea; lesions involving the putamen are more prone to cause dystonia than those involving the globus pallidus; infrequently they cause abulia or disinhibition, and in this case, the globus pallidus is usually involved; however, bilateral lesions involving the globus pallidus do not often cause parkinsonism but it is common for them to cause behavioural disturbances.

Motor symptomatology

Where necrosis of the caudate nucleus and putamen has been present for a long period there is retrograde degeneration of the cortico-striate fibres both in the subcallosal fasciculus and in the external capsule [42]. As the pyramidal motor system, the basal ganglia-thalamocortical circuits maintain somatotopic organisation of movement-related neurons throughout the circuit [5, 99], mainly through the putamen, where neurons related to active and/or passive movements of the lower extremity are found in a long rostrocaudal extension of the dorsolateral putamen, neurons related to orofacial movements are located ventromedially, and neurons related to movements of the upper extremity are located in an intermediate position. This somatotopical distribution has the same pattern in both segments of the globus pallidus [145]. Interruption of the extrapyramidal system appears to be responsible for muscle spasticity and hyperactive deep reflexes. Involvement of the basal ganglia (including ventrobasal nuclei of the thalamus) is linked with involuntary and stereotyped movements without involving voluntary motor functions. Diseases of the basal ganglia (extrapyramidal pathology) result in profound movement disorders, which cause changes in motor functions:

1. Spontaneous hyperkinetic disorders such as are seen in Huntington's disease [61, 84] or Tourette's syndrome
2. Diminished movement (akinesia or hypokinesia) such as is seen in Parkinson's disease [189] and progressive supranuclear palsy [112]
3. Motor stereotypies [22]

Moreover, lesions of the basal ganglia result in changes in muscle tone (muscular rigidity), fine resting tremor, postural disorders and athetosis (vermicular movements of the distal extremities). Other involuntary movement

disorders include such symptoms as hyperactivity, dyskinesia or hemiballismus, depending of the position of the lesion in the basal ganglia. A progressive generalised chorea and dementia with neostriatal neuronal loss and gliosis (vascular chorea) has been described [13]. The variable tremor and rigidity of Wilson's disease is associated with degeneration of the lenticular nucleus (putamen and globus pallidus) resulting from a disorder of copper metabolism [59]. Other degenerative changes in the basal ganglia (caudate nucleus and putamen) are associated with complex stereotypies [119], dystonia after head trauma [41, 43, 105], involuntary movements of choreiform type (jerky, rapid and purposeless movements involving axial and proximal musculature of the extremities), athetoid-type movements (slow, sinuous and aimless movements involving distal limb musculature) [43] or ballism [45]. Indeed, the best pathological correlation is that of hemiballismus: uncontrollable sudden, flailing gross movements of the proximal limb musculature of one or both limbs on the contralateral side of the lesion [91]. It is associated with lesion of the contralateral subthalamic nucleus of Luys [121] or its connections, but there are even reports of hemiballismus without subthalamic lesion but with a lenticular lacunar infarct, probably with internal globus pallidus involvement [122, 123]. Subthalamic nucleus (and internal globus pallidus) are important pacemakers of the basal ganglia [156]. The cardinal motor signs found in Parkinson's disease (akinesia, rigidity and resting tremor) are generally attributed to the loss of dopaminergic input to the striatum that results from the degeneration of the substantia nigra pars compacta [50]. Chronic treatment with levodopa and/or dopaminergic agonists results in unacceptable side effects, such as dyskinesia or hyperkinesia [189]. This reversal of symptoms is caused by the imbalance of the direct and indirect basal ganglia pathways required for coordinated movements [72, 96]. In recent years, new therapeutic approaches have included:

1. Pharmacological strategies with different dopamine-receptor agonists [114] and new surgical approaches such as
2. Transplantation of dopaminergic neurons [56]
3. Lesions or deep brain stimulation of the subthalamic nucleus or of the internal globus pallidus [65, 97]

Behavioural disturbances

Basal ganglia and the adjacent structures play a part in predicting future events, reinforcing wanted behaviour and suppressing unwanted behaviour [172] and are involved in shifting attentional sets and in high-order processes of movement initiation [17] as well as in spatial working memory [158]. As functions of the basal ganglia include cognitive and emotional aspects, clinical symptomatology is not restricted to the motor system; some psychological, disorders of mood and thought disturbances are known, including depression, schizophrenia and obsessive compulsive disorder [2, 61, 155, 173]. Basal ganglia–thalamocortical circuits reveal functional subdivisions of the oculomotor, prefrontal and cingulate circuits [5, 19, 58, 66], which have an important role in attention, learning and potentiation of behaviour-guiding rules [171, 197, 198], making them comparable to the somatotopic channels within the motor circuit, which are involved in the programming and control of movement. In the Bhatia and Marsden study [12] of a total of 240 patients with basal ganglia lesions, 111 had some type of behavioural disorder with aphasic and dysarthric dysfunction, abulia, depression, disinhibited behaviour and acute confusional state after haemorrhage into the caudate (even if this last is probably the consequence of a widespread brain dysfunction due to intraventricular bleeding). Aphasia has been described without haemorrhagic lesions when lesions are located in the caudate nucleus [8, 35, 100, 101]. Frontal lobe syndrome [183], psychic akinesia [100] and obsessive compulsive disturbances [101] have been described when bilateral lesions are established. The caudate nucleus contributes to memory [197], learning [93, 130], cognitive [165, 171] and behaviour [172] functions; its bilateral damage leads to apathy, decreased recent memory and reduced initiative and spontaneity [128].

Despite the voluminous literature available on it, the role of basal ganglia in health and disease remains controversial. Moreover, as basal ganglia are closely located to the thalamus and they have intimate and highly specific afferent and efferent connections with cerebral cortex and thalamus, basal ganglia should not be viewed as nuclei with a role independent of both structures [130, 153].

Acknowledgements The authors would like to express their acknowledgement to their colleagues of the Experimental Neurology and Neurosurgery Group. M.T.H. also wishes to thank Professor Agid, Dr. Hirsch, Dr. Obeso and Dr. Percheron for their scientific support and helpful advice on these topics. Drawings in the figures have been performed by C. Barcia. This work was supported by grants nos. FIS 99/1392 and FEDER 1FD97–1931.

References

1. Adams NC, Lozsadi DA, Guillery RW (1997) Complexities in the thalamocortical and corticothalamic pathways. Eur J Neurosci 9:204–209
2. Afifi AK (1994) Basal ganglia: functional anatomy and physiology, II. J Child Neurol 9:352–361
3. Akopyan NS, Baklavadzhyan OG, Sarkisyan NV (2000) The effects of the mediodorsal nucleus of the thalamus on respiratory neurons of the medulla oblongata and respiration in rats in conditions of hypoxia. Neurosci Behav Physiol 30:449–453
4. Al-Chaer ED, Lawand NB, Westlund KN, Willis WD (1996) Visceral nociceptive input into the ventral posterolateral nucleus of the thalamus: a new function for the dorsal column pathway. J Neurophysiol 76:2661–2674
5. Alexander GE, Crutcher MD (1990) Functional architecture of basal ganglia circuits: neural substrates of parallel processing. Trends Neurosci 13:266–271
6. Alexander GE, DeLong MR, Strick PL (1986) Parallel organization of functionally segregated circuits linking basal ganglia and cortex. Annu Rev Neurosci 9:357–381
7. Anastasopoulos D, Bronstein AM (1999) A case of thalamic syndrome: somatosensory influences on visual orientation. J Neurol Neurosurg Psychiatry 67:390–394
8. Barat M, Mazaux JM, Bioulac B, Giroire JM, Vital C, Arné L (1981) Troubles du langage de type aphasique et lésions putamino-caudées. Observation anatomo-clinique. Rev Neurol 137:343–356
9. Barbas H (2000) Connections underlying the synthesis of cognition, memory, and emotion in primate prefrontal cortices. Brain Res Bull 52:319–330
10. Barriga F, Ruiz Dominguez JA, Velayos JL (1997) Insomnio familiar: una enfermedad priónica humana que abre las puertas a un mayor conocimiento del tálamo. Rev Med Univ Navarra 41:224–228
11. Berendsen HW, Gronewegen HJ (1991) Restricted cortical terminal fields of the midline and intralaminar thalamic nuclei in the rat. Neuroscience 42:73–102
12. Bhatia KP, Marsden CD (1994) The behavioural and motor consequences of focal lesions of the basal ganglia in man. Brain 117:859–876
13. Bhatia KP, Lera G, Luthert PJ, Marsden CD (1994) Vascular chorea: case reported with pathology. Mov Disord 9:447–450
14. Bickle J, Bernstein M, Heatley M, Worley C, Stiehl S (1999) A functional hypothesis for LGN-V1-TRN connectivities suggested by computer simulation. J Comput Neurosci 6:251–261
15. Blomqvist A, Ericson AC, Craig AD, Broman J (1996) Evidence for glutamate as a neurotransmitter in spinothalamic tract terminals in the posterior region of owl monkeys. Exp Brain Res 108:33–44
16. Blomqvist A, Zhang ET, Craig AD (2000) Cytoarchitectonic and immunohistochemical characterization of a specific pain and temperature delay, the posterior portion of the ventral medial nucleus, in the human thalamus. Brain 123:3601–3619
17. Boussaoud D, Kermadi I (1997) The primate striatum: neuronal activity in relation to spatial attention versus motor preparation. Eur J Neurosci 9:2152–2168
18. Brandt T, Steinke W, Thic A, Pessin MS, Caplan LR (2000) Posterior cerebral artery territory infarcts: clinical features, infarcts topography, causes and outcome. Multicenter results and a review of the literature. Cerebrovasc Dis 10:170–182
19. Brown J, Bullock D, Grossberg S (1999) How the basal ganglia use parallel excitatory and inhibitory learning pathways to selectively respond to unexpected rewarding cues. J Neurosci 19:10502–10511
20. Buchel C, Josephs O, Rees G, Turner R, Frith CD, Friston KJ (1998) The functional anatomy of attention to visual motion. A functional MRI study. Brain 121:1281–1294
21. Burgel U, Schormann T, Schleicher A, Zilles K (1999) Mapping of histologically identified long fiber tracts in human cerebral hemispheres to the MRI volume of a reference brain: position and spatial variability of the optic radiation. Neuroimage 10:489–499
22. Canales JJ, Graybiel AM (2000) A measure of striatal function predicts motor stereotypy. Nat Neurosci 3:377–383
23. Canavan AGM, Nixon PD, Passingham RE (1989) Motor learning in monkeys (*Macaca fascicularis*) with lesions in motor thalamus. Exp Brain Res 77:113–126
24. Chandler MJ, Hobbs SF, Fu QG, Kenshalo DR, Blair RW, Foreman RD (1992) Responses of neurons in ventroposterolateral nucleus of primate thalamus to urinary bladder distension. Brain Res 571:26–34
25. Chen W, Zhu XH (2001) Correlation of activation sizes between lateral geniculate nucleus and primary visual cortex in humans. Magn Reson Med 45:202–205
26. Chen W, Zhu XH, Thulborn KR, Ugurbil K (1999) Retinotopic mapping of lateral geniculate nucleus in humans using functional magnetic resonance imaging. Proc Natl Acad Sci USA 96:2430–2434
27. Churchill L, Kalivas PW (1999) The involvement of the mediodorsal nucleus of the thalamus and the midbrain extrapyramidal area in locomotion elicited from the ventral pallidum. Behav Brain Res 104:63–71
28. Cola MG, Gray DN, Seltzer B, Cusick CG (1999) Human thalamus: neurochemical mapping of inferior pulvinar complex. Neuroreport 16:3733–3738
29. Collins P, Wilkinson LS, Everitt BJ, Robbins TW, Roberts AC (2000) The effect of dopamine depletion from the caudate nucleus of the common marmoset (*Callithrix jacchus*) on tests of prefrontal cognitive function. Behav Neurosci 114:3–17
30. Cossete M, Levesque M, Parent A (1999) Extrastriatal dopaminergic innervation of human basal ganglia. Neurosci Res 34:51–54
31. Cox CL, Huguenard JR, Prince DA (1997) Nucleus reticularis neurons mediate diverse inhibitory effects in thalamus. Proc Natl Acad Sci USA 94:8854–8859
32. Crabtree JW, Collingridge GL, Isaac JT (1998) A new intrathalamic pathway linking modality-related nuclei in the dorsal thalamus. Nat Neurosci 1:389–394
33. Craig AD, Bushnell MC, Zhang ET, Blomqvist A (1994) A thalamic nucleus specific for pain and temperature sensation. Nature 372:770–773
34. Crutchfield JS, Sawaya R, Meyers CA, Moore BD (1994) Postoperative mutism in neurosurgery. Report of two cases. J Neurosurg 81:115–121
35. Damasio AR, Damasio H, Rizzo M, Varney N, Gersh F (1982) Aphasia with non-hemorrhagic lesion in the basal ganglia and internal capsule. Arch Neurol 39:15–24
36. Davis KD, Tasker RR, Kiss ZH, Hutchison WD, Dostrovsky JO (1995) Visceral pain evoked by thalamic microstimulation in humans. Neuroreport 26:369–374

37. Davis KD, Lozano RM, Manduch M, Tasker RR, Kiss ZH, Dostrovsky JO (1999) Thalamic relay site for cold perception in humans. J Neurophysiol 81:1970–1973
38. Debakan A (1953) Human thalamus. An anatomical developmental and pathological study. I. Division of the human adult thalamus into nuclei by use of the cytomyeloarchitectonic method. J Comp Neurol 99:639–667
39. Debakan A (1954) Human thalamus. An anatomical developmental and pathological study: development of the human thalamic nuclei. J Comp Neurol 100:63–97
40. De Biasi S, Amadeo A, Spreafico R, Rustioni A (1994) Enrichment of glutamate immunoreactivity in lemniscal terminals in the ventropostero lateral thalamic nucleus of the rat: an immunogold and WGA-HRP study. Anat Rec 240:131–140
41. Demierre B, Rondot P (1983) Dystonia caused by putamino-capsulo-caudate vascular lesions. J Neurol Neurosurg Psychiatry 46:404–409
42. Denny-Brown D (1962) The basal ganglia and their relation to disorders of movement. Oxford University Press, London
43. Denny-Brown D (1968) Symposium on disease of the basal ganglia. Nature of dystonia. Rev Bras Med 25:769–773
44. De Salles AA, Bittar GT Jr (1994) Thalamic pain syndrome: anatomic and metabolic correlation. Surg Neurol 41:147–151
45. Destée A, Muller JP, Vermersch P, Pruvo JP, Warot P (1990) Hemiballisme. Hemichorée. Infarctus striatal. Rev Neurol 146:150–152
46. Duncan GH, Kupers RC, Marchand S, Villemure JG, Gybels JM, Bushnell MC (1998) Stimulation of human thalamus for pain relief: possible modulatory circuits revealed by positron emission tomography. J Neurophysiol 80:3326–3330
47. Engelborghs S, Marien P, Martin JJ, De Deyn PP (1998) Functional anatomy, vascularisation and pathology of the human thalamus. Acta Neurol Belg 98:252–265
48. Engelborghs S, Marien P, Pickutt BA, Verstraeten S, De Deyn PP (2000) Loss of psychic self-activation after paramedian bithalamic infarction. Stroke 31:1762–1765
49. Ergenzinger ER, Glasier MM, Hahm JO, Pons TP (1998) Cortically induced thalamic plasticity in the primate somatosensory system. Nat Neurosci 1:226–229
50. Fearnley JM, Lees AJ (1991) Ageing and Parkinson's disease: substantia nigra regional selectivity. Brain 114:2283–2301
51. Fenelon G, Francois C, Percheron G, Yelnik J (1991) Topographic distribution of the neurons of the central complex (centre median-parafascicular complex) and of other thalamic neurons projecting to the striatum in macaques. Neuroscience 45:495–510
52. Ferrier D (1876) The functions of the brain. London
53. Fischer C, Bognar L, Turjman F, Lapras C (1995) Auditory evoked potentials in a patient with a unilateral lesion of the inferior colliculus and medial geniculate body. Electroencephalogr Clin Neurophysiol 96:261–267
54. Foreman RD (1999) Mechanism of cardiac pain. Annu Rev Physiol 61:143–147
55. François C, Yelnik J, Percheron G, Fenelon G (1994) Topographic distribution of the axonal endings from the sensorimotor and associative striatum in the macaque pallidum and substantia nigra. Exp Brain Res 102:305–318
56. Freed CR, Greene PE, Breeze RE, Tsai WY, DuMouchel W, Kao R, Dillon S, Winfield H, Culver S, Trojanowski JQ, Eidelberg D, Fahn S (2001) Transplantation of embryonic dopamine neurons for severe Parkinson's disease. N Engl J Med 34:710–719
57. Fukutake T, Hattori T (1998) Auditory illusions caused by a small lesion in the right medial geniculate body. Neurology 51:1469–1471
58. Gerfen CR (1984) The neostriatal mosaic: compartmentalization of corticostriatal input and striatonigral output systems. Nature 311:461–464
59. Giagheddu M, Tamburini G, Piga M, Tacconi P, Giagheddu A, Serra A, Siotto P, Satta L, Demelia L, Marrosu F (2001) Comparison of MRI, EEG, EPs and ECD-SPECT in Wilson's disease. Acta Neurol Scand 103:71–81
60. Glass M, Dragunow M, Faull RL (1997) Cannabinoid receptors in the human brain: a detailed anatomical and quantitative autoradiographic study in the fetal, neonatal and adult human brain. Neuroscience 77:299–318
61. Graveland GA, Williams RS, DiFiglia M (1985) Evidence for degenerative and regenerative changes in neostriatal spiny neurons in Huntington's disease. Science 227:770–773
62. Groenewegen HJ, Berendse HW (1994) The specificity of the "nonspecific" midline and intralaminar thalamic nuclei. Trends Neurosci 17:52–57
63. Guillery RW (1995) Anatomical evidence concerning the role of the thalamus in corticocortical communication: a brief review. J Anat 187:583–592
64. Guillery RW, Feig SL, Lozsadi DA (1998) Paying attention to the thalamic reticular nucleus. Trends Neurosci 21:28–32
65. Guridi J, Herrero MT, Luquin MR, Guillen J, Ruberg M, Laguna J, Vila M, Javoy-Agid F, Agid Y, Hirsch EC, Obeso JA (1996) Subthalamotomy in parkinsonian monkeys. Behavioural and biochemical analysis. Brain 119:1717–1727
66. Haber SN, Kunishio K, Mizobuchi M, Lynd-Balta E (1995) The orbital and medial prefrontal circuit through the primate basal ganglia. J Neurosci 15:4851–4867
67. Hassler R (1982) Architectonic organization of the thalamic nuclei. In: Schaltenbrand G, Walker AE (eds) Stereotaxy of the human brain – anatomical, physiological and clinical applications, 2nd edn. Thieme, Stuttgart, pp 140–180
68. Hayase N, Miyashita N, Endo K, Narabayasi H (1998) Neuronal activity in GP and Vim of parkinsonian patients and clinical changes of tremor through surgical interventions. Stereotact Funct Neurosurg 71:20–28
69. Henderson JM, Carpenter K, Cartwright H, Halliday GM (2000) Loss of thalamic intralaminar nuclei in progressive supranuclear palsy and Parkinson's disease: clinical and therapeutic implications. Brain 123:1410–1421
70. Herrero MT, Hirsch EC, Kastner AM, Ruberg M, Luquin MR, Laguna J, Javoy-Agid F, Obeso JA, Agid Y (1993) Does neuromelanin contribute to the vulnerability of catecholaminergic neurons in monkeys intoxicated with MPTP? Neuroscience 56:499–511
71. Herrero MT, Augood SJ, Hirsch EC, Javoy-Agid F, Agid Y, Obeso JA, Emson PC (1995) Effects of l-DOPA on preproenkephalin and preprotachykinin gene expression in the MPTP-treated monkeys striatum. Neuroscience 68:1189–1198
72. Herrero MT, Augood SJ, Asensi H, Hirsch EC, Agid Y, Obeso JA, Emson PC (1996) Effects of l-DOPA-therapy on dopamine D2 receptor mRNA expression in the striatum of MPTP-intoxicated parkinsonian monkeys. Mol Brain Res 42:149–155
73. Herrero MT, Levy R, Ruberg M, Javoy-Agid F, Luquin MR, Agid Y, Hirsch EC, Obeso JA (1996) Glutamic acid decarboxylase mRNA expression in medial and lateral pallidal neurons in the MPTP-treated monkeys and patients with Parkinson's disease. Adv Neurol 69:209–216

74. Herrero MT, Levy R, Ruberg M, Luquin MR, Villares J, Guillen J, Faucheux B, Javoy-Agid F, Guridi J, Agid Y, Obeso JA, Hirsch EC (1996) Consequence of nigrostriatal denervation and l-DOPA therapy on the expression of glutamic acid decarboxylase messenger RNA in the pallidum. Neurology 47:219–224
75. Hess WR (1954) Diencephalon: autonomic and extrapyramidal functions. Grune and Stratton, New York
76. Hirai T, Jones EG (1989) A new parcellation of the human thalamus on the basis of histochemical staining. Brain Res Rev 14:1–34
77. Holsapple JW, Preston JB, Strick PL (1991) The origin of thalamic inputs to the hand representation in the primary motor cortex. J Neurosci 11:2644–2654
78. Hoover JE, Strick PL (1993) Multiple output in the basal ganglia. Science 259:819–821
79. Houk JC, Wise SP (1995) Distributed modular architectures linking basal ganglia, cerebellum, and cerebral cortex: their role in planning and controlling action. Cereb Cortex 2:95–110
80. Huguenard JR (1999) Neuronal circuitry of thalamocortical epilepsy and mechanisms of antiabsence drug action. Adv Neurol 79:991–999
81. Illinsky IA, Kultas-Illinsky K (1987) Sagittal cytoarchitectonic maps of the *Macaca mulatta* thalamus with a revised nomenclature of motor-related nuclei validated by observations on their connectivity. J Comp Neurol 262:331–364
82. Illinsky IA, Ambardekar AV, Kultas-Illinsky K (1999) Organization of projections from the anterior pole of the nucleus reticularis thalami (NRT) to subdivisions of the motor thalamus: light and electron microscopic studies in the rhesus monkey. J Comp Neurol 409:369–384
83. Jeanmonod D, Magnin M, Morel A (1994) Chronic neurogenic pain and the medial thalamotomy. Schweiz Rundsch Med Prax 83:702–707
84. Joel D (2001) Open interconnected model of basal ganglia-thalamocortical circuitry and its relevance to the clinical syndrome of Huntington's disease. Mov Disord 16:407–423
85. Johnson MD, Ojemann GA (2000) The role of the human thalamus in language and memory: evidence from electrophysiological studies. Brain Cogn 42:218–230
86. Jones EG (1985) The thalamus. Plenum, New York
87. Jones EG (1990) Correlation and revised nomenclature of ventral nuclei in the thalamus of human and monkey. Stereotact Funct Neurosurg 54/55:1–20
88. Jones EG (2000) Cortical and subcortical contributions to activity-dependent plasticity in primate somatosensory cortex. Annu Rev Neurosci 23:1–37
89. Kalashnikova LA, Gulevskaya TS, Kashina EM (1999) Disorders of higher mental functions due to single infarctions in the thalamus and in the area of the thalamofrontal tracts. Neurosci Behav Physiol 29:397–403
90. Kastner AM, Herrero MT, Hirsch EC, Guillen J, Luquin MR, Javoy-Agid F, Obeso JA, Agid Y (1994) Decreased tyrosine hydroxylase content in the dopaminergic neurons of MPTP-intoxicated monkeys: effect of levodopa and GM1 ganglioside therapy. Ann Neurol 36:206–214
91. Kim JS, Suh DC (2001) Hemiballismhemichorea and posterior communicating artery stenosis. Eur Neurol 45:182–183
92. Kiss ZH, Dostrovsky JO, Tasker RR (1994) Plasticity in human somatosensory thalamus as a result of deafferentation. Stereotact Funct Neurosurg 62:153–163
93. Knowlton BJ, Mangels JA, Squire LR (1996) A neostriatal habit learning system in humans. Science 273:1399–1402
94. Kölliker A (1896) Handbuch der Gewebelehre des Menschen. Nervensysteme des Menschen und der Thiere, vol 2, 6th edn. Engelman, Leipzig
95. Kolomiets BP, Deniau JM, Mailly P, Ménétrey A, Glowinski J, Thierry AM (2001) Segregation and convergence of information flow through the cortico-subthalamic pathways. J Neurosci 21:5764–5772
96. Korstzewa RM (1995) Dopamine receptor sensitivity. Neurosci Biobehav Rev 19:1–17
97. Krause M, Fogel W, Heck A, Hacke W, Bonsanto M, Trenkwalder C, Tronnier V (2001) Deep brain stimulation for the treatment of Parkinson's disease: subthalamic nucleus versus globus pallidus internus. J Neurol Neurosurg Psychiatry 70:464–470
98. Kretschmann HJ, Weinrich W (1998) Neurofunctional systems. 3D reconstructions with correlated neuroimaging. Thieme, Stuttgart, pp 110–117
99. Kunzle H (1977) Projections from the primary somatosensory cortex to basal ganglia and thalamus in the monkey. Exp Brain Res 30:481–491
100. Laplane D, Baulac M, Widlocher D, Dubois B (1984) Pure psychic akinesia with bilateral lesions of basal ganglia. J Neurol Neurosurg Psychiatry 47:377–385
101. Laplane D, Levasseur M, Pillon B, Dubois B, Baulac M, Mazoyer B, Tran Dinh S, Sette G, Danze F, Baron JC (1989) Obsessive-compulsive and other behavioural changes with bilateral basal ganglia lesions. A neuropsychological, magnetic resonance imaging and positron tomography study. Brain 112:699–725
102. Lawrence AD (2000) Error correction and the basal ganglia: similar computations for action, cognition and emotion? Trends Cogn Sci 4:365–367
103. Lee MS, Marsden CD (1994) Movement disorders following lesions of the thalamus or subthalamic region. Mov Disord 9:493–507
104. Lee MS, Rinne JO, Ceballos-Baumann A, Thompson PD, Marsden CD (1994) Dystonia after head trauma. Neurology 44:1374–1378
105. Lenz FA, Byl NN (1999) Reorganization in the cutaneous core of the human thalamic principal somatic sensory nucleus (Ventral caudal) in patients with dystonia. J Neurophysiol 82:3204–3212
106. Lenz FA, Dougherty PM (1998) Neurons in the human thalamic somatosensory nucleus (Ventralis caudalis) respond to innocuous cool and mechanical stimuli. J Neurophysiol 79:2227–2230
107. Lenz FA, Jaeger CJ, Seike MS, Lin YC, Reich SG, DeLong MR, Vitek JL (1999) Thalamic single neuron activity in patients with dystonia: dystonia-related activity and somatic sensory reorganization. J Neurophysiol 82:2372–2392
108. Lera G, Scipioni O, Garcia S, Cammarota A, Fischbein G, Gershanik O (2000) A combined pattern of movement disorders resulting from posterolateral thalamic lesions of a vascular nature: a syndrome with clinico-radiologic correlation. Mov Disord 15:120–126
109. Levy R, Herrero MT, Ruberg M, Villares J, Faucheux B, Guridi J, Guillen J, Luquin MR, Javoy-Agid F, Obeso JA, Agid Y, Hirsch EC (1995) Effects of nigrostriatal denervation and l-DOPA therapy on the GABAergic neurons of the striatum in MPTP-treated monkeys and Parkinson's disease. Eur J Neurosci 7:1199–1209
110. Levy R, Hazrati LN, Herrero MT, Vila M, Hassani OK, Mouroux M, Ruberg M, Asensi H, Agid Y, Feger J, Obeso JA, Parent A, Hirsch EC (1997) Re-evaluation of the functional anatomy of the basal ganglia in normal and parkinsonian states. Neuroscience 76:335–343

111. Liu X, Aziz TZ, Miall RC, Rowe J, Alusi SH, Bain PG, Stein JF (2000) Frequency analysis of involuntary movements during wrist tracking: a way to identify MS patients with tremor who benefit from thalamotomy. Stereotact Funct Neurosurg 74:53–62
112. Litvan I, Dickson DW, Buttner-Ennever JA, Delacourte A, Hutton M, Dubois B, Golbe LI, Hallet M, Schellenberg GD, Standert D, Brooks DJ, Price D, et al (2000) Research goals in progressive supranuclear palsy. Mov Disord 15:446–458
113. Lozano A, Linazasoro G (2000) Surgical treatment of dystonia. Rev Neurol 30:1073–1076
114. Lozano AM, Lang AE, Hutchinson WD, Dostrowsky JO (1998) New developments in understanding the etiology of Parkinson's disease and its treatment. Curr Opin Neurobiol 8:783–790
115. Lumer ED, Edelman GM, Tononi G (1997) Neural dynamics in a model of the thalamocortical system. I. Layers, loops and the emergence of fast synchronous rhythms. Cereb Cortex 7:207–227
116. Lytton WW, Destexhe A, Sejnowski TJ (1996) Control of slow oscillations in the thalamocortical neuron: a computer model. Neuroscience 70:673–684
117. Macchi G, Bentivoglio M (1999) Is the "nonspecific" thalamus still "nonspecific"? Arch Ital Biol 137:201–226
118. Macchi G, Jones EG (1997) Towards an agreement on terminology of nuclear and subnuclear divisions of the motor thalamus. J Neurosurg 86:670–685
119. Maraganore DM, Lees AJ, Marsden CD (1991) Complex stereotypies after right putaminal infarction: a case report. Mov Disord 6:358–361
120. Marsden JF, Ashby P, Limousin-Dowsey P, Rothwell JC, Brown P (2000) Coherence between cerebellar thalamus, cortex and muscle in man: cerebellar thalamus interactions. Brain 123:1459–1470
121. Martin JP (1927) Hemichorea resulting from a local lesion of the brain (the syndrome of the body of Luys). Brain 50:637–651
122. Martin JP (1957) Hemichorea (hemiballismus) without lesions in the corpus Luysii. Brain 80:1–10
123. Mas JL, Launay M, Derouesne C (1987) Hemiballism and CT-documented lacunar infarct in the lenticular nucleus. J Neurol Neurosurg Psychiatry 50:104–105
124. Miyai I, Suzuki T, Kang J, Volpe BT (2000) Improved functional outcome in patients with hemorrhagic stroke in putamen and thalamus compared with those with stroke restricted to the putamen or thalamus. Stroke 31:1365–1369
125. Moreaud O, Pellat J, Charnallet A, Carbonell S, Brennen T (1995) Déficit de la production et de l'apprentissage des noms propres après lésion ischemique tubero-thalamique gauche. Rev Neurol 151:93–99
126. Morel A, Magnin M, Jeanmonod D (1997) Multiarchitectonic and stereotactic atlas of the human thalamus. J Comp Neurol 387:588–630
127. Morrow TJ, Casey KL (1992) State-related modulation of thalamic somatosensory responses in the awake monkey. J Neurophysiol 67:305–317
128. Mrabet A, Mrad-Ben Hammouda I, Abroug Z, Smiri W, Haddad A (1994) Infarctus bilatéral des noyaux caudés. Rev Neurol 150:67–69
129. Munkle MC, Waldvogel HJ, Faull RL (1999) Calcium-binding protein immunoreactivity delineates the intralaminar nuclei of the thalamus in the human brain. Neuroscience 90:485–491
130. Nakano K (2000) Neural circuits and topographical organization of the basal ganglia and related regions. Brain Dev 22:S5-S16
131. Nakano K, Kayahara T, Tsutsumi T, Ushiro H (2000) Neural circuits and functional organization of the striatum. J Neurol 247:1–15
132. Nauta WJH, Mehler WR (1966) Projections from the lentiform nucleus in the monkey. Brain Res 1:3–42
133. Neau JP, Bogousslavsky J (1996) The syndrome of posterior choroidal artery territory infarction. Ann Neurol 39:779–788
134. Nisbet AP, Foster OJ, Kingsbury A, Lees AJ, Marsden CD (1994) Nitric oxide synthase mRNA expression in human subthalamic nucleus, striatum and globus pallidus: implications for basal ganglia function. Mol Brain Res 22:329–332
135. Nowinski WL (1998) Anatomical targeting in functional neurosurgery by the simultaneous use of multiple Schaltenbrand-Wahren brain atlas microseries. Stereotact Funct Neurosurg 71:103–116
136. Ogawa K, Toita T, Kakinohana Y, Tominaga D, Miyagi K, Yoshii Y, Horikawa A, Sawada S (1999) A patient with improvement in short-term memory disturbance brought about by radiation therapy for germinoma involving Papez circuit. Radiat Med 17:317–322
137. Ohye C (1986) Rôle des noyaux thalamiques dans l'hypertonie et le tremblement de la maladie de Parkinson. Rev Neurol 142:362–367
138. Ohye C, Hirai T, Miyazaki M, Shibazaki T, Nakajima H (1982) Vim thalamotomy for the treatment of various kinds of tremor. Appl Neurophysiol 45:245–250
139. Ohye C, Shibazaki T, Hirai T, Kawashima Y, Hirato M, Matsumura M (1985) Plastic change of the thalamic organization in the cases with tremor after stroke. Appl Neurophysiol 61:488–500
140. Olszewski J (1952) The thalamus of *Macaca Mulatta*. An atlas for use with the stereotaxic instruments. Karger, Basel
141. Ongur D, Price JL (2000) The organization of networks within the orbital and medial prefrontal cortex of rats, monkeys and humans. Cereb Cortex 10:206–219
142. Pakkenberg B (1993) Leucotomized schizophrenics loss neurons in the mediodorsal nucleus. Neuropathol Appl Neurobiol 19:373–380
143. Papez JW (1937) A proposed mechanism of emotion. Arch Neurol Psychiatry 38:725–743
144. Pare D, Steriade M (1993) The reticular thalamic nucleus projects to the contralateral dorsal thalamus in macaque monkey. Neurosci Lett 154:96–100
145. Parent A (1990) Extrinsic connections of the basal ganglia. Trends Neurosci 13:254–258
146. Parent A, Hazrati LN (1993) Anatomical aspects of information processing in primate basal ganglia. Trends Neurosci 16:111–116
147. Parent A, Sato F, Wu Y, Gauthier J, Lévesque M, Parent M (2000) Organization of the basal ganglia: the importance of axonal collateralization. Trends Neurosci 23:S20-S27
148. Parker A, Eacott MJ, Gaffan D (1997) The recognition memory deficit caused by mediodorsal thalamic lesion in non-human primates: a comparison with rhinal cortex lesion. Eur J Neurosci 9:2423–2431
149. Pepin EP, Auray-Pepon L (1993) Selective dorsolateral frontal lobe dysfunction associated with diencephalic amnesia. Neurology 43:733–741
150. Percheron G (1982) Arterial supply of the thalamus. In: Schaltenbrand G, Walker AE (eds) Stereotaxy of the human brain, 2nd edn. Thieme, Stuttgart, pp 218–232

151. Percheron G, Francois C, Talbi B, Meder JF, Fenelon G, Yelnik J (1991) The primate motor thalamus analyzed with reference to subcortical afferent territories. Stereotact Funct Neurosurg 93:32–41
152. Percheron G, Fenelon G, Leroux-Hugon V, Feve A (1994) History of the basal ganglia system. Slow development of a major cerebral system. Rev Neurol 150:543–554
153. Percheron G, François C, Yelnik J, Fénelon G, Talbi B (1994) The basal ganglia related system of primates: definition, description and informational analysis. In: Percheron G, Mckenzie JS, Feger J (eds) The basal ganglia IV. Plenum, New York, pp 3–20
154. Percheron G, François C, Talbi B, Yelnik J, Fénelon G (1996) The primate motor thalamus. Brain Res Rev 22:93–181
155. Pitman RK (1987) A cybernetic model of obsessive-compulsive psychopathology. Comp Psychiatry 28:334–343
156. Plenz D, Kitai ST (1999) A basal ganglia pacemaker formed by the subthalamic nucleus and external globus pallidus. Nature 400:677–682
157. Poellinger A, Thomas R, Lio P, Lee A, Makris N, Rosen BR, Kwong KK (2001) Activation and habituation in olfaction – an fMRI study. Neuroimage 13:547–560
158. Postle BR, Corkin S, Jonides J, Smith EE, Growdon JH (1997) Spatial, but not object, delayed response is impaired in early Parkinson's disease. Neuropsychology 11:171–179
159. Puelles L, Rubinstein JL (1993) Expression patterns of homeobox and other putative regulatory genes in the embryonic mouse forebrain suggest a neuromeric organization. Trends Neurosci 16:472–479
160. Raeva S (1986) Localization in human thalamus of units triggered during "verbal commands", voluntary movements and tremor. Electroencephalogr Clin Neurophysiol 63:160–173
161. Ralston HJ, Ralston DD (1992) The primate dorsal spinothalamic tract: evidence for a specific termination in the posterior nuclei (Po/SG) of the thalamus. Pain 48:107–118
162. Ralston HJ, Ralston DD (1994) Medial lemniscal and spinal projections to the macaque thalamus: an electron microscopic study of differing GABAergic circuitry serving thalamic somatosensory mechanisms. J Neurosci 14:2485–2502
163. Ray JP, Price JL (1993) The organization of projections from the mediodorsal nucleus of the thalamus to orbital and medial prefrontal cortex in macaque monkeys. J Comp Neurol 337:1–3
164. Ray JP, Russchen FT, Fuller TA, Price JL (1992) Sources of presumptive glutamatergic/aspartatergic afferents to the mediodorsal nucleus of the thalamus in the rat. J Comp Neurol 320:435–456
165. Redgrave P, Prescott TJ, Gurney K (1999) The basal ganglia: a vertebrate solution to the selection problem? Neuroscience 89:1009–1023
166. Rogers RD, Andrews TC, Grasby PM, Brooks DJ, Robbins TW (2000) Contrasting cortical and subcortical activations produced by attentional-set shifting and reversal learning in humans. J Cogn Neurosci 12:142–162
167. Rolls ET (1994) Neurophysiology and cognitive functions of the striatum. Rev Neurol 150:648–660
168. Sadikot AF, Parent A, François C (1992) Efferent connections of the centromedian and parafascicular thalamic nuclei in the squirrel monkey: a PHA-L study of subcortical projections. J Comp Neurol 315:137–159
169. Sakai ST, Patton K (1993) Distribution of cerebellothalamic and nigrothalamic projections in the dog: a double anterograde tracing study. J Comp Neurol 330:183–194
170. Sakai ST, Stepniewska I, Qi HX, Kaas JH (2000) Pallidal and cerebellar afferents to pre-supplementary motor area thalamocortical neurons in the owl monkey: a multiple labeling study. J Comp Neurol 417:164–180
171. Salinas E, Opris I, Zainos A, Hernandez A, Romo R (2000) Motor and non motor roles of the cortico basal ganglia circuitry. In: Miller R, Wickens J (eds) Brain dynamics and the striatal complex. Conceptual advances in brain research, vol 1. Harwood Academic, pp 237–255
172. Schultz W, Dayan P, Montague PR (1997) A neural substrate of prediction and reward. Science 275:1593–1599
173. Selden N, Geula C, Hersch L, Mesulam MM (1994) Human striatum: chemoarchitecture of the caudate nucleus, putamen and ventral striatum in health and Alzheimer's disease. Neuroscience 60:621–636
174. Selemon LD, Goldman-Rakic PS (1985) Longitudinal topography and interdigitation of corticostriatal projections in the rhesus monkey. J Neurosci 5:776–794
175. Shintani S, Tsuruoka S, Shiigai T (2000) Pure sensory stroke caused by a cerebral hemorrhage: clinical-radiologic correlations in seven patients. Am J Neuroradiol 21:515–520
176. Sidibe M, Bevan MD, Bolam JP, Smith Y (1997) Efferent connections of the internal globus pallidus in the squirrel monkey. I. Topography and synaptic organization of the pallidothalamic projection. J Comp Neurol 382:323–347
177. Smith Y, Kieval JZ (2000) Anatomy of the dopamine system in the basal ganglia. Trends Neurosci 23:S28–S33
178. Smith Y, Bennett BD, Bolam JP, Parent A, Sadikot AF (1994) Synaptic relationships between dopaminergic afferents and cortical or thalamic input in the sensorimotor territory of the striatum in monkey. J Comp Neurol 344:1–19
179. Smythies J (1997) The functional neuroanatomy of awareness: with a focus on the role of various anatomical systems in the control of intermodal attention. Conscious Cogn 6:455–481
180. Steriade M, Contreras D, Amzica F, Timofeev I (1996) Synchronization of fast (30–40 Hz) spontaneous oscillations in intrathalamic and thalamocortical networks. J Neurosci 16:2788–2808
181. Strafella A, Ashby P, Munz M, Dostrovsky JO, Lozano AM, Lang AE (1997) Inhibition of voluntary activity by thalamic stimulation in humans: relevance for the control of tremor. Mov Disord 12:727–737
182. Strick PL (1985) How do basal ganglia and cerebellum gain access to the cortical motor areas? Behav Brain Res 18:107–123
183. Strub RL (1989) Frontal lobe syndrome in a patient with bilateral globus pallidus lesions. Arch Neurol 46:1024–1027
184. Tan EK (1999) Parkinson's disease surgery: advances and future strategies. Int J Clin Pract 53:623–626
185. Taniwaki T, Tagawa K, Sato F, Iino K (2000) Auditory agnosia restricted to environmental sounds following cortical deafness and generalized auditory agnosia. Clin Neurol Neurosurg 102:156–162
186. Tasker RR, Kiss ZH (1995) The role of the thalamus in functional neurosurgery. Neurosurg Clin N Am 6:73–104
187. Turner RS, DeLong MR (2000) Corticostriatal activity in primary motor cortex of the macaque. J Neurosci 20:7096–7108
188. Van der Werf YD, Witter MP, Uylings HB, Jolles J (2000) Neuropsychology of infarctions in the thalamus: a review. Neuropsychologia 38:613–627

189. Vidailhet M, Bonnet AM, Marconi R, Gouider-Khouja N, Agid Y (1994) Do parkinsonian symptoms and levodopa-induced dyskinesias start in the foot? Neurology 44:1613–1616
190. Vila M, Herrero MT, Levy R, Faucheux B, Ruberg M, Guillen J, Luquin MR, Guridi J, Javoy-Agid F, Agid Y, Obeso JA, Hirsch EC (1996) Consequences of nigrostriatal denervation on the GABAergic neurons of substantia nigra *pars reticulata* and superior colliculus in parkinsonian syndromes. Neurology 46:802–809
191. Vila M, Levy R, Herrero MT, Ruberg M, Faucheux B, Obeso JA, Agid Y, Hirsch EC (1996) Consequences of nigrostriatal denervation on the functioning of the basal ganglia in human and non-human primates: an in situ hybridization study of cytochrome oxidase subunit I mRNA. J Neurosci 17:765–773
192. Visser PJ, Krabbendam L, Verhey FR, Hofman PA, Verhoeven WM, Tuinier S, Wester A, Den Berg YW, Goessens LF, Werf YD, Jolles J (1999) Brain correlates of memory dysfunction in alcoholic Korsakoff's syndrome. J Neurol Neurosurg Psychiatry 67:774–778
193. Von Donkelaar P, Stein JF, Passingham RE, Miall RC (1999) Neuronal activity in the primate motor thalamus during visually triggered and internally generated limb movements. J Neurophysiol 82:934–945
194. Wessel K, Vieregge P, Kessler C, Kompf D (1994) Thalamic stroke: correlation of clinical symptoms, somatosensory evoked potentials and CT findings. Acta Neurol Scand 90:167–173
195. Whittle IR, O'Sullivan M, Sellar R, Ironside J (1994) Teaching image-guided stereotactic methodology and functional neuroanatomy of the thalamus and pallidum: a simple ex vivo technique. Br J Neurosurg 8:579–583
196. Willis WD, Westlund KN (1997) Neuroanatomy of the pain system and of the pathways that modulate pain. J Clin Neurophysiol 14:2–31
197. Wise S (1996) The role of the basal ganglia in procedural memory. Semin Neurosci 8:39–46
198. Wise SP, Murray EA, Gerfen CR (1996) The frontal cortex-basal ganglia system in primates. Crit Rev Neurobiol 10:317–356
199. Yamashiro K, Tomiyama N, Ishida A, Terada Y, Mukawa J, Yoshii Y, Tasker RR, Albe-Fessard D (1997) Characteristics of neurons with high-frequency discharge in the central nervous system and their relationship to chronic pain. Experimental and clinical investigations. Stereotact Funct Neurosurg 68:149–154
200. Yan W, Suga N (1998) Corticofugal modulation of the midbrain frequency map in the bat auditory system. Nat Neurosci 1:54–58
201. Yoshida M (1992) Neurophysiological atlas created by mapping of clinical responses elicited on electrical stimulation of the human thalamus. Stereotact Funct Neurosurg 58:39–44
202. Young RF, Jacques DS, Rand RW, Copcutt BR (1994) Medial thalamotomy with the Leksell gamma knife for treatment of chronic pain. Acta Neurochir Suppl 62:105–110
203. Zhang Y, Suga N, Yan J (1997) Corticofugal modulation of frequency processing in bat auditory system. Nature 387:900–903