

Brain Science

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The 3-Dimensional Atlas of the Marmoset Brain

Reconstructible in Stereotaxic Coordinates

 Springer

Brain Science

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The “Brain Science Series” provides critical and comprehensive discussions of the most significant areas of neuroscience research, written by scientific leaders and authorities. Each volume in the series presents the latest and most complete information on its respective subject, making it an unrivalled reference source. To analyze brain functions that have been preserved through evolution, a reductive approach based on gene manipulation using models such as genetically modified rodents were mainly used. At the same time, to analyze high-order brain functions that are uniquely acquired only in non-human primates and humans, analyses of complex behaviors using a psychological approach were mainly adopted. The Brain Science Series focuses on clarifying the operating principles of the neural circuitry governing the human mind, as well as the accompanying molecular mechanisms.

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Preface

The 3-Dimensional Atlas of the Marmoset Brain: Reconstructible in Stereotaxic Coordinates is aimed to provide accurate, comprehensive, and convenient reference for usages of the “freely rotatable three dimensional combined Nissl-stained and MRI digital data of the marmoset brain,” available at the Neuroinformatics Japan Center website:

http://brainatlas.brain.riken.jp/marmoset/modules/xoonips/listitem.php?index_id=66.

The key features of the original 3D digital data and of this atlas are as follows:

- (a) The original digital datasets are *freely rotatable* in three dimensions, thus expected to be useful for any disciplines and anatomical interest, using any coordinate system.
- (b) Combined Nissl-stained and MRI images are obtained from the same marmoset to allow cross-modality matched references for multiple usages.
- (c) 86 Horizontal Series of Images with Neurosurgical Plane (based on the actual data), with more accuracy and resolution (Chap. 2) than the web-based digital images.
- (d) 32 Coronal Series of Images with Neurosurgical Plane (reproduced from the brain model) (Chap. 3).
- (e) 10 Parasagittal Series of Images with Neurosurgical Plane (reproduced from the brain model) (Chap. 4).
- (f) 3 Omnidirectionally Sliceable Planes (reproduced from the brain model) (Chap. 5):
 - (A) Modified Horizontal Slices, three plates, to represent the thalamic and cortical visual structures, i.e., the dorsal lateral geniculate nucleus and primary visual cortex (V1), respectively, in the same plane
 - (B) Modified Coronal Slices, three plates, to represent the thalamic and cortical somatosensory structures, i.e., the ventral posteromedial nucleus (VPM) and ventral posterolateral nucleus (VPL) and primary somatosensory cortex (S1), S2, and S3, respectively, in the same plane
 - (C) Modified Parasagittal Slices, one plate, to represent the continuous descending fiber system from the primary motor cortex to the spinal cord, i.e., the internal capsule, cerebral peduncle, longitudinal

fasciculus of the pons, and pyramidal tract of the medulla oblongata, in the same plane

These are just a few examples of the major benefit of this digital atlas. The readers can create their own plane and download from URL and subsidize additional accuracy using this atlas.

- (g) In order to provide higher resolution structures to match systematic accuracy for supplementation of the digital data on the website, additional information are included. They are (1) Nomenclature, (2) List of Brain Structures in Hierarchical Order, and (3) Index of Abbreviations, together with 143 useful Bibliography as of 2016.
- (h) Horsley-Clarke's stereotaxic coordinates were adopted in the present atlas.

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Also, the contributors and editors are happy for figures in this atlas as well as on the website to be reproduced in other publications, but they expect their work to be suitably acknowledged.

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Introduction

1

Tsutomu Hashikawa, Atsushi Iriki,
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The common marmoset (*Callithrix jacchus*), a New World monkey, has been used in a variety of biomedical studies as an animal model of nonhuman primates. It seems to be anticipated that there will be rapid surge in the interest of primate biology, since genome of this species has been sequenced recently (Marmoset Genome Sequencing and Analysis Consortium 2014). The evolution of gene manipulation technologies suggests that the use of the common marmoset will increase in future studies. In addition, the marmoset can be a useful animal model in neuroscience

research. This is because among the primates, the common marmoset is available with mature adults being small in size (300–500 g), and these monkeys are easier to handle in a laboratory setting. They show high fertility, giving birth to nonidentical twins twice in a year, and earlier sexual maturity (~15 months), so that certain genetic aspects of neural functions can be analyzed in primates as well (Sasaki et al. 2009), which is important given that genetic studies that have taken place so far have been conducted mostly in mice. Furthermore, they have a well-developed brain sharing similar characteristics across various primate species (Paxinos et al. 2012). Common features of their brain structures make rather direct comparisons possible among the species. A combination of knowledge of research on Old World primates and new insights from genetic approaches in marmosets will provide a better and more comprehensive understanding of brain functions.

In neuroscience research, brain atlases can be of useful assistance in identifying and analyzing neurological structures. For such purpose, several atlases have been published for the marmoset brain (Paxinos et al. 2012; Stephan et al. 1980).

Recently, in addition to histological analyses, magnetic resonance imaging (MRI) technology has become a routine means to specify functional areas in the brain and requires interactive structural information for image acquisition. To fit in with current research demands, a newly developed brain atlas has been proposed recently (Hashikawa

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et al. 2015), which is a volume-rendered model and web accessible at the following URL: http://brainatlas.brain.riken.jp/marmoset/modules/xoonips/listitem.php?index_id=66.

The manual for the use of the software, SG-eye viewer, can be obtained in the same link.

In this book, series of pictures and line drawings of horizontally sectioned common marmoset brain slices, which are basic data for a brain model, are carried out with histological information from Nissl preparations and radiological information from MRI data at almost the same sectional levels as Nissl preparations. Since there are some technical limitations in reconstructing the model, fine subdivisions of the brain structures were not achieved in the model. Instead the information in the plates of this book is finer than that in the model, in terms of the brain area delineations. This book can be a reliable reference for the identification of the brain structures in both histological and radiological studies in the common marmoset.

Materials and Methods

Histology

For production of an axial-free steric brain atlas, a brain from the common marmoset monkey (*Callithrix jacchus*; female; 2.3 years old; weighing 310 g) was obtained from the Central Institute for Experimental Animals (CIEA), Kawasaki, Japan. The use of animals in the experiments followed the guideline approved at CIEA. Under deep anesthesia with intramuscularly administered ketamine hydrochloride (10 mg/kg body weight) and intraperitoneally administered sodium pentobarbital (40 mg/kg body weight), the animal was perfused through the left ventricle with physiological saline followed by 4% paraformaldehyde in 0.1 M phosphate buffer (PB, pH 7.4). Prior to histological preparation, MRI was performed on this animal (see below). After perfusion, the skull with the animal's brain was placed onto a stereotaxic apparatus, in which the horizontal axis was set on the orbitomeatal line, and reference marks were made on the right side with carbon shafts (0.5 mm in diameter). The horizontal axis passed through the coronal plane 3.5 mm rostral to the interaural

line and horizontal zero plane, 2.0 mm and 2.5 mm lateral to the midline, respectively. The brain with references was embedded in 10% gelatin in 0.1 M PB. Histological sections with plane parallel to the neurosurgically horizontal axis were cut on a freezing microtome at 50 μ m thickness, and all sections were mounted on glass slides and stained with thionine. Photomicrographs were taken from the sections with a virtual slide scanner VS-100 (Olympus, Tokyo, Japan), and the imaged data were processed using Photoshop (Adobe, CA, USA). DATA was then imported into SG-eye software (Fiatlux, Tokyo, Japan), a newly developed program used for these types of studies (Kumazawa-Manita et al. 2013). SG-eye constructs 3D model by surface rendering and GPU-accelerated volume ray casting. The volume ray casting algorithm comprises four steps; ray casting, sampling, shading, and compositing. In ray casting, a ray of sight is cast through the volume for each pixel of images. There are several functions such as position adjusting, editing mask images, labeling, and annotating each brain region in SG-eye. Finally, a 3D digital volume-rendered brain model was constructed from the data obtained from histological sections.

MRI

To get images under MRI for the marmoset standard brain (go to following URL: <http://brainatlas.brain.riken.jp/marmoset/modules/xoonips/detail.php?id=004>) and the brain used for the above histological preparation, the animals were anesthetized with intramuscular administration of ketamine and xylazine followed by a tracheal administration of a mixture of oxygen and isoflurane, and MRI scans using a 7-T PhamaScan 70/16 MRI scanner (Bruker, Germany) were performed (see Hikishima et al. 2011, for more detail).

Nomenclature

In this book, English anatomical terms were adopted. The nomenclature, abbreviation, and delineation of brain structures conformed to that used in the marmoset brain atlas of Paxinos et al. (2012).

List of Brain Structures in Hierarchical Order

Following is a list of brain structures. On the right rows their abbreviations and colors assigned to individual structures are indicated.

WHOLE BRAIN

1. FOREBRAIN (TELENCEPHALON and DIENCEPHALON)

1.1. TELENCEPHALON

1.1.1. OLFACTORY BULB

- Accessory olfactory bulb
- Anterior olfactory nucleus
- External plexiform layer of the accessory olfactory bulb
- External plexiform layer of the olfactory bulb
- Glomerular layer of the accessory olfactory bulb
- Glomerular layer of the olfactory bulb
- Granule cell layer of the accessory olfactory bulb
- Granule cell layer of the olfactory bulb
- Mitral cell layer of the accessory olfactory bulb
- Mitral cell layer of the olfactory bulb
- Olfactory bulb
- Olfactory nerve layer

1.1.2. CEREBRUM/CEREBRAL CORTEX

- Olfactory cortex
 - Olfactory tubercle
 - Islands of Calleja
 - Islands of Calleja/major island
 - Tenia tecta
- Cortical areas
 - Agranular insular cortex
 - Anterior intraparietal area of cortex
 - Areas 1 and 2 of cortex
 - Area 3a of cortex (primary somatosensory)
 - Area 3b of cortex (primary somatosensory)
 - Area 4 of cortex/parts a and b (primary motor)
 - Area 4 of cortex/part c (primary motor)
 - Area 6 of cortex/dorsocaudal part
 - Area 6 of cortex/dorsorostral part
 - Area 6 of cortex/medial (supplementary motor) part
 - Area 6 of cortex/ventral/part a
 - Area 6 of cortex/ventral/part b
 - Area 8a of cortex/dorsal part
 - Area 8a of cortex/ventral part
 - Area 8b of cortex
 - Area 8 of cortex/caudal part
 - Area 9 of cortex
 - Area 10 of cortex
 - Area 11 of cortex
 - Area 13a of cortex
 - Area 13b of cortex
 - Area 13 of cortex/lateral part
 - Area 13 of cortex/medial part
 - Area 14 of cortex/caudal part
 - Area 14 of cortex/rostral part
 - Area 19 of cortex/dorsointermediate part

WHOLE









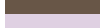












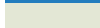


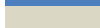






















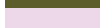


FORE












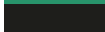











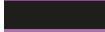

























- TEL
- OLB
- AOB
- AON
- EPIA
- EPI
- GIA
- GI
- GrA
- GrO
- MiA
- Mi
- OB
- ON

CER

- OlfC
- Tu
- ICj
- ICjM
- TT
- CorA
- AI
- AIP
- A1/2
- A3a
- A3b
- A4ab
- A4c
- A6DC
- A6DR
- A6M
- A6Va
- A6Vb
- A8aD
- A8aV
- A8b
- A8C
- A9
- A10
- A11
- A13a
- A13b
- A13L
- A13M
- A14C
- A14R
- A19DI



Area 19 of cortex/medial part	A19M	
Area 23a of cortex	A23a	
Area 23b of cortex	A23b	
Area 23c of cortex	A23c	
Area 23 of cortex/ventral part	A23V	
Area 24a of cortex	A24a	
Area 24b of cortex	A24b	
Area 24c of cortex	A24c	
Area 24d of cortex	A24d	
Area 25 of cortex	A25	
Area 29a-c of cortex	A29a-c	
Area 29d of cortex	A29d	
Area 30 of cortex	A30	
Area 31 of cortex	A31	
Area 32 of cortex	A32	
Area 32 of cortex/ventral part	A32V	
Area 35 of cortex	A35	
Area 36 of cortex	A36	
Area 45 of cortex	A45	
Area 46 of cortex/dorsal part	A46D	
Area 46 of cortex/ventral part	A46V	
Area 47 (old 12) of cortex/lateral part	A47L	
Area 47 (old 12) of cortex/medial part	A47M	
Area 47 (old 12) of cortex/orbital part	A47O	
Auditory cortex/anterolateral area	AuAL	
Auditory cortex/caudolateral area	AuCL	
Auditory cortex/caudomedial area	AuCM	
Auditory cortex/caudal parabelt area	AuCPB	
Auditory cortex/middle lateral area	AuML	
Auditory cortex/primary area	AuA1	
Auditory cortex/rostral area	AuR	
Auditory cortex/rostral parabelt	AuRPB	
Auditory cortex/rostromedial area	AuRM	
Auditory cortex/rostrotemporal lateral area	AuRTL	
Auditory cortex/rostrotemporal medial area	AuRTM	
Auditory cortex/rostrotemporal part	AuRT	
Dysgranular insular cortex	DI	
Entorhinal cortex	Ent	
Faciola cinereum	FC	
Fundus of superior temporal sulcus area of cortex	FST	
Granular insular cortex	GI	
Gustatory cortex	Gu	
Indusium griseum	IG	
Insular proisocortex	IPro	
Lateral intraparietal area of cortex	LIP	
Medial intraparietal area of cortex	MIP	
Medial superior temporal area of cortex	MST	
Navicular nucleus of the basal forebrain	Nv	
Occipito-parietal transitional area of cortex	OPt	
Orbital periallocortex	OPAI	

Orbital proisocortex	OPro	
Parainsular cortex/lateral part	PaIL	
Parainsular cortex/medial part	PaIM	
Parasubiculum	PaS	
Parietal area PE	PE	
Parietal area PE/caudal part	PEC	
Parietal area PF	PF	
Parietal area PFG	PFG	
Parietal area PG	PG	
Parietal areas PGa and IPa (fundus of superior temporal ventral area)	PGa/IPa	
Parietal area PG/medial part	PGM	
Piriform cortex	Pir	
Piriform cortex/layer 1	Pir 1	
Piriform cortex/layer 2	Pir 2	
Piriform cortex/layer 3	Pir 3	
Presubiculum	PrS	
Proisocortical motor region (precentral opercular cortex)	ProM	
Prostriate area	ProSt	
Prosubiculum	ProS	
Retroinsular area	Rel	
Secondary somatosensory cortex/external part	S2E	
Secondary somatosensory cortex/internal part	S2I	
Secondary somatosensory cortex/parietal rostral area	S2PR	
Secondary somatosensory cortex/parietal ventral area	S2PV	
Superior temporal rostral area	STR	
Supracallosal subiculum	SS	
Temporal area TE1	TE1	
Temporal area TE2	TE2	
Temporal area TE3	TE3	
Temporal area TE/occipital part	TEO	
Temporal area TF	TF	
Temporal area TF/occipital part	TFO	
Temporal area TH	TH	
Temporal area TL	TL	
Temporal area TL/occipital part	TLO	
Temporal proisocortex	TPro	
Temporo-parieto-occipital association area (superior temporal polysensory cortex)	TPO	
Temporopolar proisocortex	TPPro	
Temporoparietal transitional area	TPt	
Ventral intraparietal area of cortex	VIP	
Visual area 1	V1	
Visual area 2	V2	
Visual area 3 (ventrolateral posterior area)	V3	
Visual area 3A (dorsoanterior area)	V3A	
Visual area 4 (ventrolateral anterior area)	V4	
Visual area 4/transitional part	V4T	
Visual area 5 (middle temporal area)	V5	
Visual area 6 (dorsomedial area)	V6	
Visual area 6A (posterior parietal medial area)	V6A	
Hippocampal formation	HipF	