HANDBOOK OF CLINICAL NEUROLOGY

Series Editors:
MICHAEL J. AMINOFF, FRANÇOIS BOLLER, AND DICK F. SWAAB

208

3rd Series

CEREBRAL ASYMMETRIES

Edited by:
COSTANZA PAPAGNO
PAUL CORBALLIS

ELSEVIER

CEREBRAL ASYMMETRIES

HANDBOOK OF CLINICAL NEUROLOGY

Series Editors

MICHAEL J. AMINOFF, FRANÇOIS BOLLER, AND DICK F. SWAAB

VOLUME 208

ELSEVIER

CEREBRAL ASYMMETRIES

Series Editors

MICHAEL J. AMINOFF, FRANÇOIS BOLLER, AND DICK F. SWAAB

Volume Editors

COSTANZA PAPAGNO AND PAUL CORBALLIS

VOLUME 208

3rd Series

ELSEVIER

ELSEVIER
Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
125 London Wall, London EC2Y 5AS, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

Copyright © 2025 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Publisher's note: Elsevier takes a neutral position with respect to territorial disputes or jurisdictional claims in its published content, including in maps and institutional affiliations.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

With respect to any drug or pharmaceutical products identified, readers are advised to check the most current information provided (i) on procedures featured or (ii) by the manufacturer of each product to be administered, to verify the recommended dose or formula, the method and duration of administration, and contraindications. It is the responsibility of practitioners, relying on their own experience and knowledge of their patients, to make diagnoses, to determine dosages and the best treatment for each individual patient, and to take all appropriate safety precautions.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

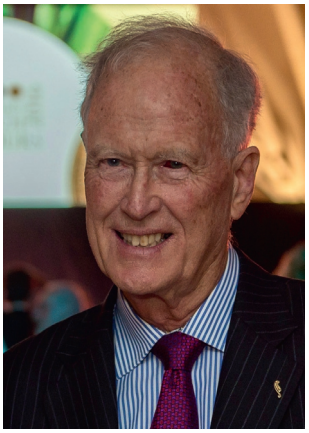
ISBN: 978-0-443-15646-5

For information on all Elsevier publications
visit our website at https://www.elsevier.com/books-and-journals

Publisher: Stacy Masucci
Acquisitions editor: Megan McManus
Editorial Project Manager: Kristi Anderson
Production Project Manager: Omer Mukthar
Cover Designer: Christian Bilbow

Typeset by STRAIVE, India

In Memoriam



Michael Corballis

Emeritus Professor Michael Corballis passed away while this volume on cerebral asymmetries—for which he had agreed to serve as volume editor—was being developed and he helped in its planning. Michael was a preeminent scholar in human cognitive neuroscience and neuropsychology. In a career that spanned seven decades, he made significant contributions to various research areas, including perception, attention, memory and mental time travel, language origins, recursive thought, and mind wandering. Central to his endeavors were the questions of human uniqueness and the role of hemispheric asymmetry in enabling and shaping the human mind.

Michael was born on September 10, 1936. His university education coincided with the foundation of academic departments of psychology in his native New Zealand, and with the evolution and expansion of neuropsychology internationally. He was among the first students to study psychology at Victoria University (Wellington) and the University of Auckland before moving to Montreal for his doctoral training at McGill University. Montreal had emerged as a hub of neuropsychologic thought, and the notion of grounding psychology in the anatomy and physiology of the brain inspired Michael's early interest in how cerebral lateralization might underlie asymmetries in perception and action.

Cerebral asymmetry remained a key focus after Michael returned to New Zealand in 1977. He was particularly interested in how apparently unrelated asymmetries might have common origins or lead to unexpected consequences. In *The Lopsided Ape* (1991), he reflected on the strong lateralization of both language and fine motor control, and advanced the hypothesis that language may have its origin in gesture rather than speech—an idea that would motivate much of his thinking for the next three decades.

Michael authored or coauthored more than 300 scientific articles, 14 books, and many commentaries, published reviews, and public-interest pieces. His status as a scholar was recognized through numerous fellowships and awards, including the New Zealand Order of Merit in 2002 and the Rutherford Medal from the Royal Society of New Zealand in 2016.

Aside from his prolific scholarship, Michael will be remembered for his urbane wit, humility, and generosity of spirit. He passed away peacefully on November 13, 2021, following a brief battle with cancer. He was predeceased by Barbara, his wife of 58 years, and is survived by his sons Paul and Timothy, and three granddaughters, Simone, Natasha, and Lena.

Photo by Paul Corballis.

Michael Aminoff
Francois Boller
Paul Corballis
Dick F. Swaab
September 2024

Handbook of Clinical Neurology, Vol. 208 (3rd series)
Cerebral Asymmetries
C. Papagno and P. Corballis, Editors
https://doi.org/10.1016/B978-0-443-15646-5.00005-1
Copyright © 2025 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Chapter 23

Cerebellar asymmetries

CAROLINE NETTEKOVEN[1,2*] AND JÖRN DIEDRICHSEN[1,2,3]

[1]*Western Institute for Neuroscience, Western University, London, ON, Canada*
[2]*Department of Computer Science, Western University, London, ON, Canada*
[3]*Department of Statistical and Actuarial Sciences, Western University, London, ON, Canada*

Abstract

The cerebellum is a subcortical structure tucked underneath the cerebrum that contains the majority of neurons in the brain, despite its small size. While it has received less attention in the study of brain asymmetries than the cerebrum, structural asymmetries in the cerebellum have been found in cerebellar volume that mirror cerebral asymmetries. Larger cerebellar structures have been reported on the right compared to the left, either for the whole cerebellar hemisphere or the anterior part of the cerebellum, with the latter accompanied by a left increase in the posterior cerebellum. Cerebellar asymmetries are considered evolutionary recent and have been observed prenatally and in early development. Both asymmetries in anterior–posterior divisions and specific lobules have been linked to handedness and cognitive abilities, in particular language. Functional lateralization in the cerebellum varies across motor and cognitive functions, with language activation predominantly localized in the right hemisphere, contralateral to cerebral activation. Meanwhile, working memory and executive functions are not lateralized to one hemisphere. New neuroimaging methods and resources, including a symmetric functional atlas of the cerebellum that enables precision mapping, open novel avenues for exploring cerebellar asymmetries and answering questions about the developmental timeline, relationships to behavior, and clinical relevance.

INTRODUCTION

The cerebellum, or "little brain," is a small structure situated underneath the much larger cerebrum. Despite only making up 10% of the total brain mass, the cerebellar cortex holds 80% of all neurons (Azevedo et al., 2009) and when fully unfolded has a surface area of 78% of the neocortex (Sereno et al., 2020). The cerebellum supports a multitude of functions, including motor, executive, social, linguistic, and emotional processes. Studies of functional lateralization, particularly of higher-order cognitive functions such as language, often prioritize the cerebrum over the cerebellum. Similarly, studies of structural asymmetries have largely focused on the cerebrum, leaving many questions about cerebellar structural and circuitry asymmetries unanswered. This is partially driven by difficulties in imaging the cerebellum and a lack of tools necessary for careful investigations of cerebellar functional asymmetries. Still, studies to date provide a picture of cerebellar organization that is broadly symmetric, but includes fine hemispheric differences, some of which mirror cerebral asymmetries. Here, we review asymmetries in cerebellar structure, function, and neurochemistry. We also consider technical challenges in studying cerebellar asymmetries and outline recent advances addressing these limitations, enabling future in-depth studies of cerebellar asymmetries.

STRUCTURAL ASYMMETRIES

Broad cerebellar structure

The cerebellum consists of two hemispheres that are connected through the vermis, a worm-like midline structure. The cerebellum sits within the posterior fossa and connects to the brainstem via three pairs of peduncles: the superior, middle, and inferior peduncle. The inferior cerebellar peduncle and middle cerebellar peduncle contain mainly afferent projections to the cerebellum from the spinal cord and the cerebrum, respectively. The inferior peduncle also contains efferent projections from the cerebellum to the spinal cord. The superior peduncle primarily transports efferent fibers from the cerebellum, projecting to the cerebrum. Cerebellar afferents and efferents cross over to the contralateral cerebral hemisphere in the brainstem. In general, the cerebellum therefore connects to the contralateral cerebral hemisphere and is concerned with inputs from the ipsilateral side of the body.

*Correspondence to: Caroline Nettekoven, Department of Computer Science, Western Institute for Neuroscience, Western University, London, ON, Canada. Tel: +1-519-6612111x86057, Fax: +1-519-661-3613, E-mail: cr.nettekoven@gmail.com

The tightly folded cerebellar cortex is commonly divided along broad anatomic divisions, the fissures, into 10 lobules and denoted I–X according to the Larsell nomenclature (Larsell and Jansen, 1973; Schmahmann et al., 2000). Lobules I–V form the anterior cerebellum, lobules VI–IX the posterior cerebellum, and lobule X forms the flocculonodular lobe of the cerebellum. Because lobules VII and VIII are the two largest lobules in the human cerebellum (Diedrichsen and Zotow, 2015), many studies split them into two sections (VIIA and VIIB, as well as VIIIA and VIIIB), and lobule VIIA is split again into Crus I and Crus II.

Neuroimaging studies have identified gross asymmetries in cerebellar structure in children (Holland et al., 2014) and across the adult lifespan (Herve et al., 2006; Fan et al., 2010; Bernard and Seidler, 2013; Kang et al., 2015). While some found an overall larger right hemisphere of the cerebellum (Herve et al., 2006; Fan et al., 2010; Kang et al., 2015), others reported this volume increase on the right for only some cerebellar lobules (Kavaklioglu et al., 2017). However, some studies fail to show any structural asymmetries in the cerebellum (Gocmen-Mas et al., 2009; Ertekin et al., 2013). The earliest report of cerebellar structural asymmetry divided the cerebellum into an anterior and a posterior section according to coronal MRI slices acquired in 15 right-handed and 8 left-handed participants (Snyder et al., 1995). The authors found that in the anterior cerebellum, the right hemisphere was significantly larger than the left, whereas in the posterior cerebellum the left was bigger than the right. A similar pattern had previously been described for the neocortex (LeMay, 1976), with right anterior structures (e.g., frontal pole) extending more anteriorly and left posterior structures (e.g., occipital pole) protruding more posteriorly. This is despite the cerebellum primarily projecting to the contralateral cerebral hemisphere, which could suggest an opposite pattern of asymmetry.

Handedness

When first reporting cerebellar structural asymmetry (Snyder et al., 1995), also found a link to handedness: while all 23 participants showed an overall similar asymmetry pattern, it was more pronounced in right-handed people. A later study of 19 monozygotic female adult twins confirmed some of the structural asymmetries in the cerebellum, with the anterior cerebellum (lobules I–V) being larger on the right, but near symmetry in the posterior cerebellum (lobules VI–VIIB) (Rosch et al., 2018). The anterior cerebellar asymmetry was stronger in right-handed than left-handed twins, potentially reflecting an experience-dependent maintenance of higher growth rates in the right hemispheric cerebellum. However, differences in the definition of regions of interest between the first report, where sections were divided by coronal slice, and the more precise definition in the later study based on a lobular atlas (Diedrichsen, 2006), make a direct comparison difficult. Furthermore, the purported relationship between cerebellar asymmetry and handedness was not replicated in a large-scale study of 2226 participants (Kavaklioglu et al., 2017), but a recent investigation of over 37,000 participants associated handedness with whole-brain asymmetry patterns that included the cerebellum. Directly comparing left- and right-handed participants revealed that right-handers showed larger lobules VIIIA and VIIIB in the right cerebellar hemisphere and larger Crus I and Crus II in the left cerebellar hemisphere (Saltoun et al., 2023).

Evolutionary and developmental studies

Cerebellar structural asymmetry seems to have emerged recently in evolution, as it is only observed in modern humans—*Homo sapiens*—but not in *Homo erectus* or *Homo neanderthalensis* (Zhang and Wu, 2021). This is in contrast to cerebral asymmetries, which emerged earlier, appearing already in *Homo erectus* and *Homo neanderthalensis* (Holloway and De La Costelareymondie, 1982; Li et al., 2018).

During gestation, the cerebellum grows more quickly than any other brain region, increasing 34-fold from weeks 18–39. Early in gestation, the left cerebellar hemisphere is larger than the right, but the right shows an accelerated growth curve, nearly overtaking the left by week 39 (Andescavage et al., 2017). During the first 3 months after birth, the cerebellum again shows the fastest growth, more than doubling in size (Holland et al., 2014). During this time, the right cerebellar hemisphere is larger than the left. Cerebellar asymmetry does not depend on sex in the first 3 months of life (Holland et al., 2014), though there is some evidence for an interaction between sex and cerebellar structural asymmetries in children (Isıklar et al., 2023) and young adults (Fan et al., 2010).

Relationship with movement, language, and cognition

Several studies have related cerebellar structural asymmetries to language, motor, and cognitive functions. Neonatal whole-cerebellar asymmetry has been found to predict later language skills (Vassar et al., 2020), with more cerebellar asymmetry being linked to lower language scores as assessed with the Bayley Scales of Infant-Toddler Development-III (Bayley, 2006). However, cerebellar asymmetries in this study were based on rating scale assessments by radiologists, which differs substantially from the quantitative techniques used in previous studies (Holland et al., 2014; Andescavage et al., 2017). In 10-year-old children, whole cerebellar volume showed no association with language content, but correlated positively with right gray matter volume in Crus I/Crus II (Stipdonk et al., 2021). In a cohort of 48 autistic and non-autistic boys aged 6–13 with and without language impairment (autistic language impairment or specific language impairment), only those with impaired language function showed leftward lobule VIIIA asymmetry, irrespective of autism diagnosis. Non-impaired boys showed larger right lobule VIIIA volume, and language performance correlated with lobule VIIIA asymmetry across groups, with increased volume on the right relating to higher language scores (Hodge et al., 2010). Decreased cerebellar volume in the right hemisphere of 32 children with cerebellar malformations (aged 1–6) has been linked to impaired expressive language, as well as cognitive and motor impairments (Bolduc et al., 2012).

In adults, working memory task performance has been found to positively correlate with gray matter volume in left Crus I (Ding et al., 2012), and improved timing in musical performance has been associated with smaller right lobule VI volume (Baer et al., 2015). Meanwhile, increased volume of the cerebellar cortex was associated with mild cognitive impairment in a study of 400 randomly selected older adults (aged 64–70) (Cherbuin et al., 2010). Asymmetric gray matter reductions and torque have also been linked to neuropsychiatric disorders such as autism spectrum disorder, developmental dyslexia (Stoodley, 2014), and schizophrenia (Szeszko et al., 2003).

Cerebellar damage from injury, stroke, or degeneration has previously been shown to cause, in addition to the classic motor impairments, a range of non-motor symptoms. These include language deficits, anagrammatism, executive function deficits, and social and affective impairments that were termed the "Cerebellar Cognitive Affective Syndrome" (Schmahmann and Sherman, 1998). To our knowledge, there are so far no reports of Cerebellar Cognitive Affective Syndrome manifesting as lateralized to a particular hemisphere, although functions that belong to the symptom set of the syndrome certainly appear lateralized (see section Task-based asymmetries). Notably, cognitive symptoms after cerebellar damage in adults appear milder than in young children (Glickstein, 1994; Fabbro et al., 2004; Ronconi et al., 2017) and often result in a decrease in function rather than a full loss of it (Olson et al., 2023). For example, cerebellar damage to right Crus I/II appears to not result in aphasia or absence of speech, but in dysarthria (Ackermann, 2008; Stoodley et al., 2016) or agrammatism (Silveri et al., 1994).

Deep cerebellar nuclei

The cerebellar white matter envelops the deep cerebellar nuclei, which lie close to the midline in each hemisphere and receive the output generated from the cerebellar cortex. The deep cerebellar nuclei then project to the brainstem nuclei and the cerebral cortex via the thalamus. Only the flocculonodular cerebellar cortex, lobule X, deviates from this by projecting directly to the vestibular nuclei in the brainstem. As such, the deep cerebellar nuclei and the vestibular nuclei are the sole transmitters of the output from the cerebellum. The deep cerebellar nuclei include in each hemisphere along the medial-to-lateral axis, the dentate nucleus, the interpositus (consisting of globose and emboliform nuclei), and the fastigial nucleus.

Few neuroimaging studies have examined the structure of deep cerebellar nuclei due to their small size and their near invisibility in standard T1-weighted anatomic images (Diedrichsen et al., 2011). Only susceptibility-weighted images, which are not part of standard MRI protocols, provide suitable contrast for localizing the deep cerebellar nuclei, as these images are sensitive to their high iron content. A first volumetric comparison of left and right dentate nuclei reported increased volume on the right in 9 of 10 examined participants (Deoni and Catani, 2007), though this was not replicated in a later study of 23 participants (Diedrichsen et al., 2011). In postmortem sections of human brains, visual comparison of the dentate ribbon revealed left–right differences in the folding pattern of a single case, but no systematic differences.

Cytoarchitecture

While the cerebral cortex is dividable according to its cytoarchitecture, the cerebellar cortical makeup is generally remarkably uniform. The single output cell of the cerebellar cortex is the Purkinje cell. Each Purkinje cell receives inputs via two streams. First, they receive multiple inputs from multiple parallel fibers. Parallel fibers arise from the densely packed granule cells. Granule cells receive information via mossy fibers that originate in the spinal cord, medulla oblongata, and most massively from the pontine nuclei. The majority of axons exiting the neocortex for the brainstem either project directly to the pons or send a collateral there, which projects onto the granule cells (Tomasch, 1969). Granule cells then innervate Purkinje cells via parallel fibers. Second, each Purkinje cell receives input from a single climbing fiber, originating in the inferior olivary nucleus, though a single climbing fiber branches to innervate one to seven Purkinje cells.

Detailed descriptions of the cerebellar circuit have led to the development of the Marr-Albus-Ito model of cerebellar function (Eccles, 1967; Marr, 1969; Albus, 1971; Ito and Kano, 1982). This model is based on the convergence of the two input types at the Purkinje cell. First, the many inputs from parallel fibers are proposed to represent a detailed context. Second, the single climbing fiber input is proposed to represent an error, or "teaching" signal. When a Purkinje cell receives climbing fiber activation (error signal) shortly after activation of a set of parallel fibers (context), then the synaptic weights of this particular set of parallel fibers change through long-term depression (Ito and Kano, 1982). When this set of parallel fibers is activated again at this Purkinje cell, the Purkinje cell firing is reduced compared to before. The change in Purkinje cell firing leads to a change in behavior, a change in output to the deep cerebellar nuclei, and suppression of the climbing fiber input (Medina and Lisberger, 2008).

The Marr-Albus-Ito model explains a wealth of experimental data, particularly in the motor domain, and has been highly influential. However, recent studies cast doubt on a universal learning principle within the cerebellar cortex by painting a more complex picture of cerebellar circuitry (Beckinghausen and Sillitoe, 2019; Fujita et al., 2020; Busch and Hansel, 2023). In humans, Busch et al. (Busch and Hansel, 2023) showed in sagittal slices of three postmortem human brains that only 4% of human Purkinje cells have the stereotypic single dendritic branch, while 96% show a multibranched dendritic branch that bifurcates into multiple primary dendrites close to the neuron body. In mice, 15% of multibranched Purkinje cells also receive multiple climbing fiber inputs to the different dendritic branches, and some branches seemed to have locally distinct functional responses to whisker stimulation. These results show a clear divergence from the purported regularity of the cerebellar circuitry. The authors also described an anterior-to-posterior gradient in dendritic branching patterns, where the majority of Purkinje cells in lobules I–VI had

normative, single-branched dendrites and the multibranched dendrites occurred in the majority of lobule VII–X. However, left–right asymmetries in Purkinje cell branching could not be detected, as the investigation focused on sagittal slices of the mid-section of only one hemisphere, precluding a between-hemispheric comparison.

Summary

Studies of structural asymmetries in the cerebellum have largely focused on the cerebellar cortex or overall cerebellar volume rather than the cerebellar nuclei, due to its relative accessibility in neuroimaging data. Generally, studies find rightward asymmetry in the cerebellum, with increased cerebellar volume on the right anterior cerebellum and increased left volume in the posterior cerebellum. Cerebellar asymmetries seem to be evolutionary recent and appear before birth. Some links with handedness, cognitive functions, and clinical diagnosis have been reported, although little consensus has been found. This may in part be driven by differences in analysis methods and techniques used to assess cerebellar asymmetry. Some studies have divided the cerebellum along the anterior-to-posterior axis for asymmetry analysis (Snyder et al., 1995), others group lobules into cerebellar zones (Bolduc et al., 2012; Rosch et al., 2018) or use ratings from radiologists to assess cerebellar asymmetry (Stipdonk et al., 2021). Establishing consensus on cerebellar asymmetry across the heterogeneous literature is therefore difficult.

As tools for cerebellar segmentation and atlases for cerebellar parcellation have been developed, most studies now parcellate the cerebellum along lobular boundaries (Fan et al., 2010; Bernard et al., 2015; Kavaklioglu et al., 2017; Isıklar et al., 2023; Saltoun et al., 2023) based on a probabilistic group atlas of cerebellar lobules (Diedrichsen, 2006). This makes comparing results across neuroimaging studies easier. However, most researchers are interested in linking observed asymmetries to cerebellar function, relying on the assumption that different cerebellar-dependent functions can be localized to different lobules. Mapping cerebellar activity across motor and cognitive domains revealed this is not the case (King et al., 2019). Indeed, cerebellar activity usually spans several lobules, and one lobule often contains multiple functional regions. Future studies of structural asymmetry in the cerebellar cortex should therefore use symmetric regions of interest that capture functional regions when attempting to link structural asymmetries to function. For a discussion of recent advances in this realm, see section Technical considerations for studying cerebellar lateralization.

FUNCTIONAL LATERALIZATION

The cerebellum has traditionally been associated with motor function, though neuroimaging studies show cerebellar activity during a broad range of behavioral tasks, including those probing language (Petersen et al., 1989), social cognition (Van Overwalle et al., 2015), attention (Allen et al., 1997), and working memory (Marvel and Desmond, 2010). While the cerebellum has been researched extensively in motor control, the study of the cerebellar role in higher-order cognitive functions such as language is in its relative infancy.

Task-based asymmetries

A function is considered lateralized if it engages one hemisphere of the brain more than the other, of which language function is a prime example. Right-lateralization of language activation in the cerebellum, mirroring left lateralization in the cerebrum, is well established (Amunts et al., 1996; Stoodley and Schmahmann, 2009; Fedorenko et al., 2010; Haberling and Corballis, 2016; LeBel and D'Mello, 2023). Though most language studies do not focus on the cerebellum or do not cover the cerebellum during data acquisition or analysis, there are early reports of functional lateralization in the right cerebellum during language processing (Petersen et al., 1989; Raichle et al., 1994).

Using positron emission tomography, Petersen et al. (Petersen et al., 1989) were the first to show clear lateralized cerebellar activation during language processing, even when motor demands were accounted for. Subsequent studies confirmed right cerebellar activation during language processes such as semantic retrieval and prediction (Fiez et al., 1996; Moberget and Ivry, 2016; Lesage et al., 2017).

A meta-analysis of task-based fMRI studies showed that language activity primarily occurs in the right cerebellum in lobule VI, Crus I/Crus II as well as vermal lobule VIIA (Stoodley and Schmahmann, 2009). On the other hand, left-lateralized activation was found primarily for spatial tasks, located in lobule VI. However, both language and spatial tasks showed some weaker, but consistent bilateral activation, occupying a small cluster in opposite lobule VI.

To examine the relationship between language lateralization in the cerebellum and neocortex, Wang et al. (Wang et al., 2013) analyzed fMRI data acquired while participants performed a semantic decision task. In the cerebellum, participants showed strong language lateralization in the right Crus I/Crus II and in the cerebrum, in the left prefrontal cortex. Language activity lateralization in the cerebellum was correlated with language lateralization in the cerebrum: right cerebellar task lateralization correlated with left cerebral task-based language lateralization. In line with lateralization of language and spatial function, patients with left-sided cerebellar lesions showed larger impairments in attention and visuospatial tasks, but not language, fluency, or motor function (Starowicz-Filip et al., 2021). Right-sided cerebellar lesions, on the other hand, led to impaired language and verbal fluency, but also general cognitive deficits, including memory, attention, and visuospatial functions (Silveri et al., 1994; Marien et al., 1996; Leggio et al., 2000; Marien et al., 2000). A detailed analysis of cerebellar lateralization was recently provided by a voxel-wise comparison of functional profiles across 417 tasks probed in seven fMRI datasets (Nettekoven et al., 2024) (1A). Social-linguistic-spatial regions located in Crus I and Crus II (2A) showed low correlations of functional profiles, indicating strongly lateralized functional responses. On the left, these regions activated while viewing social and emotional stimuli, whereas the right regions showed far less activity in those tasks. On the right, the cerebellum responded primarily to tasks involving linguistic information, such as a word reading and theory of mind story reading task or a verb generation task. In contrast, cerebellar working memory regions in lobules VI and VII

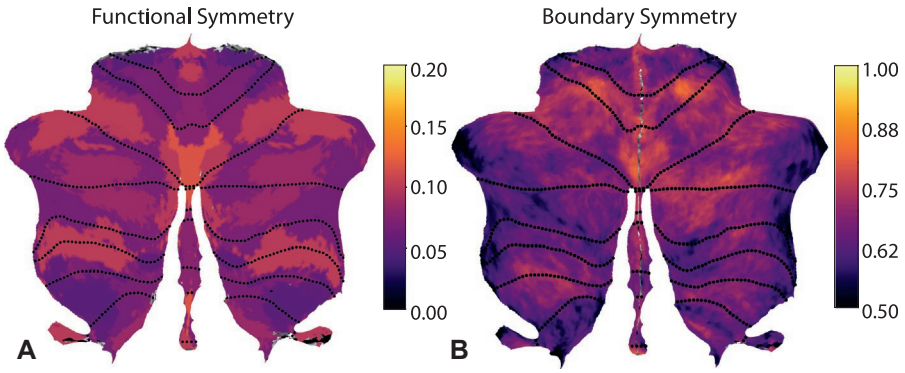


Fig. 23.1. Functional lateralization and boundary symmetry of cerebellar functional regions. Functional symmetry calculated as the correlations between the functional responses of anatomically corresponding voxel in the left and right hemispheres, averaged across participants and within each functional region (A) reveals bilateral response profiles of multiple demand regions and lateralized responses of social-linguistic-spatial regions. Boundary symmetry calculated as the correlations of the probabilistic voxel assignments between the symmetric and asymmetric versions of the atlas (B) shows symmetric boundaries in the motor regions, and asymmetric boundaries in social-linguistic-spatial regions. Reproduced from Nettekoven C, Zhi D, Shahshahani L, et al. (2024). A hierarchical atlas of the human cerebellum for functional precision mapping. Nat Commun 15: 8376. https://doi.org/10.1038/s41467-024-52371-w.

showed largely bilateral responses (Fig. 23.1A), as indicated by highly correlated functional profiles across tasks. This was despite the variety of executive function and working memory tasks in the task set, including those probing verbal working memory. Hence, while there might be some lateralization of working memory and executive function, the majority of tasks activate cerebellar working memory regions bilaterally.

Neuroimaging studies of motor and sensory tasks show sensorimotor homunculi on each side of lobules III–VI and lobule VIII (Stoodley and Schmahmann, 2009). Cerebellar activity is largely confined to the hemisphere ipsilateral to the moving effector (Saadon-Grosman et al., 2022), but bilateral for tongue and eyes (Buckner et al., 2011; Nettekoven et al., 2024). A voxel-wise comparison of the functional profiles confirmed this pattern of lateralization in cerebellar motor regions. The left and right cerebellar hand regions (M3) show low correlations of functional profiles (Fig. 23.1A). Finally, activity in the oculomotor vermis, responsible for eye movements and saccades, showed strongly bilateral responses. Therefore, while some functions are clearly lateralized in the cerebellum, such as language and social cognition, others are consistently bilateral like working memory and executive function, or exhibit laterality that appears effector-dependent such as motor functions.

In addition to having different functional profiles, boundaries between functional regions themselves can be asymmetric. The recent development of a symmetric functional atlas of the cerebellum (see section Technical considerations for studying cerebellar lateralization) allowed for the first systematic comparison of boundary symmetry in the cerebellum (Nettekoven et al., 2024). Examining the correspondence between the symmetric and asymmetric version of the atlas (Fig. 23.1A and B) across the different regions revealed that regions involved in movement and working memory functions have highly symmetric boundaries, i.e., their boundaries fall into the same place on the left and right. Among the motor regions, the oculomotor vermis M1 and the hand region M3 (Fig. 23.1A) fall particularly similar in left and right cerebellar hemisphere. Meanwhile, the social-linguistic-spatial regions have more dissimilar region boundaries between left–right region pairs, indicated by the low overall boundary symmetry in social-linguistic-spatial regions (Nettekoven et al., 2024).

Resting-state connectivity asymmetries

fMRI data acquired at rest has been used to quantify cortico-cerebellar functional connectivity and examine cerebellar lateralization in the context of cerebral lateralization (O'Reilly et al., 2010; Buckner et al., 2011; Wang et al., 2013; Wang et al., 2014). In the cerebellum, resting-state fMRI data from 1000 participants demonstrated an approximately homotopic map of cerebral connectivity networks (Buckner et al., 2011). Here, each cerebellar voxel was assigned to the cerebral resting-state network its resting-state time course correlated with the most (Buckner et al., 2011). Consistent with viral tracing studies in monkeys demonstrating that cerebral cortical areas project to the contralateral cerebellum (Kelly and Strick, 2003), cortico-cerebellar connectivity is strongest between contralateral cerebellar and cerebral regions, particularly in the motor regions (Krienen and Buckner, 2009; O'Reilly et al., 2010; Buckner et al., 2011). Resting-state and task-based fMRI data demonstrated a somatomotor map of the body including foot, hand, and tongue representations in the anterior cerebellum (Buckner et al., 2011). The task-based maps revealed that lateralization of somatomotor representations in the cerebellum varies with body part. While tongue representation is bilateral, consistent with the bilateral nature of the performed tongue movement, right foot and hand representations are lateralized, with right hand activation showing the strongest lateralization. Whether this lateralization depends on handedness to our knowledge has so far not been investigated.

Resting-state connectivity between ipsilateral and contralateral corticocerebellar regions followed a similar pattern: Hand and foot regions showed much stronger coupling contralaterally than ipsilaterally, whereas tongue regions showed no difference between ipsi- and contralateral connectivity. This echoes observations for the cerebral cortex showing the lowest inter-hemispheric connectivity

between the two hand regions and the two foot regions, and high coupling for left and right tongue representations (Thomas Yeo et al., 2011).

Technical considerations for studying cerebellar lateralization

Studies of functional lateralization often necessitate defining regions of interest in the left and right hemispheres, which are matched in location and size to control for spatial differences in signal-to-noise ratio (Yan et al., 2023). Most researchers have used anatomic subdivisions into different lobules (Schmahmann et al., 2000; Diedrichsen et al., 2009) to define regions of interest, taking advantage of the anatomic symmetry of lobules. However, lobular boundaries do not reflect functional boundaries in the cerebellum (King et al., 2019), rendering them unsuitable for functional lateralization studies. Recently, a symmetric functional atlas has been developed, using a machine learning model that learns the functional organization of the cerebellum using over 100 participants across seven fMRI studies (Nettekoven et al., 2024) (Fig. 23.2A and B). The model was constrained to learn corresponding symmetric regions, while the functional responses of the matching regions could vary between the left and right hemispheres (Zhi et al., 2025). The symmetric group atlas captured functional organization 5% less accurately than the asymmetric group atlas, which represents a small trade-off between the validity of the region boundaries and practical utility for lateralization studies.

The cerebellum poses many challenges to functional neuroimaging, but the study of cerebellar functional lateralization holds promise for answering fundamental questions about brain asymmetries. Though it suffers from lower signal-to-noise ratio, the sources of noise in the cerebellum differ from those in the cerebrum, driven by different anatomic and technical constraints. By contrasting and comparing cerebral and cerebellar asymmetries, some consensus on brain asymmetries can be established, independently of the different noise sources (Wang et al., 2013).

Summary

The cerebellum shows clear functional lateralization for some, but not all, motor and cognitive functions. Language activation is largely located in the right cerebellar hemisphere, contralateral to cerebral activation. Cerebellar functional lateralization appears to be linked to cerebral functional lateralization, handedness, and lateralization of language function. However, difficulties in aligning left and right cerebellar regions of interest for studies of functional lateralization have hindered progress in this line of research. The recent development of new methods and resources for the study of cerebellar lateralization could pave the way to more precise studies of functional asymmetries in the cerebellum.

NEUROCHEMICAL ASYMMETRIES

Few studies of neurochemical asymmetries in the cerebellum exist, primarily due to the technical challenges in measuring neurochemicals from the human cerebellum in vivo. Neurochemicals in the brain can be measured noninvasively using magnetic resonance spectroscopy (MRS). However, the use of MRS in the cerebellum is impeded by the close proximity of the cerebellum to two large sources of noise: the brainstem on the anterior side and the neck on the posterior side. The fat tissue in the neck emits a signal over 100 times stronger than brain metabolites (Rothman et al., 1993) and when MRS measurements are collected close to this fatty tissue, imperfect slice selection pulses can lead to lipid contaminations of the measured spectrum (Kreis, 2004). Placing an MRS voxel in the small, curved cerebellar hemispheres at a sufficient distance from fat tissue while maximizing the gray matter content of the voxel is therefore difficult. Similarly, areas adjacent to the brainstem can suffer from high levels of physiologic noise, driven by the cardiac and respiratory cycles (Brooks et al., 2013), which induce field inhomogeneities and reduce the quality of the MRS spectra. However, with the advent of high-field imaging and improved shimming techniques for reducing field

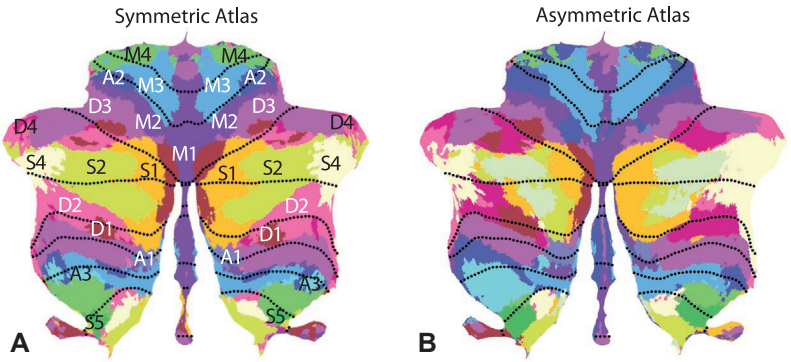


Fig. 23.2. Symmetric functional atlas of the cerebellum allows investigations of lateralization. (A) Functional atlas of the cerebellum with 32 symmetric regions. (B) Functional atlas of the cerebellum with 32 corresponding asymmetric regions. The atlas (A and B) across the different regions revealed that regions involved in movement and working memory functions have highly symmetric boundaries, i.e., their boundaries fall into the same place on the left and right. Among the motor regions, the oculomotor vermis M1 and the hand region M3 (A) fall particularly similar in the left and right cerebellar hemispheres. Meanwhile, the social-linguistic-spatial regions have more dissimilar region boundaries between left–right region pairs, indicated by the low overall boundary symmetry in social-linguistic-spatial regions (Nettekoven et al., 2024). Reproduced from Nettekoven C, Zhi D, Shahshahani L, et al. (2024). A hierarchical atlas of the human cerebellum for functional precision mapping. Nat Commun 15: 8376. https://doi.org/10.1038/s41467-024-52371-w.

inhomogeneities, there have been some investigations of cerebellar neurochemistry and their hemispheric differences.

In a first investigation study of cerebellar neurochemistry, Rae et al. (Rae et al., 1998) examined hemispheric differences in cerebellar neurochemical ratios in 14 dyslexic men and compared them to 15 male controls. In the right cerebellum of dyslexic men, the authors found decreases in the ratio of choline (Cho) to *N*-acetylaspartate (NAA), a commonly used reference metabolite (Bachtiar and Stagg, 2013) due to the high concentrations of NAA in the brain. Dyslexic men also showed significantly lower levels of creatine (Cr)/NAA in the right cerebellum compared to controls and a significant hemispheric difference in Cr/NAA concentration, whereas controls showed no hemispheric difference. The dyslexic group showed contralateral alterations in the neocortex. In the left temporoparietal lobe, dyslexic men showed significantly reduced Cho/NAA levels compared to controls and compared to their right Cho/NA levels, where controls showed equal levels.

Although motor impairments in dyslexia have been linked to a role of the cerebellum in this developmental disorder (Nicolson et al., 1995), in line with the hypothesis that cerebellar dysfunction could manifest in incoordination of eye movements during reading, no association between cerebellar neurochemistry and handedness or performance on a peg-board test was found. Nevertheless, the study provided compelling evidence for asymmetrically altered levels of cerebellar neurochemicals in dyslexia.

Tracking cerebellar neurochemical concentration over time in healthy participants has been of recent interest as a means to understanding cerebellar plasticity in healthy human function. In particular, the major inhibitory neurotransmitter γ-aminobutyric acid (GABA) has been suggested to play a fundamental role in cerebellar plasticity, since it signals information from the sole output neuron of the cerebellar cortex, the Purkinje cell, and has been implicated in parallel fiber synaptic plasticity (Orts-Del'Immagine and Pugh, 2018). Jalali et al. (Jalali et al., 2018) were the first to probe the responsiveness of the GABAergic system in the cerebellum and attempt to link it to individual differences on a task probing motor adaptation, where the cerebellum plays a key role (Diedrichsen, 2005; Graydon et al., 2005; Miall and Jenkinson, 2005). Based on previous work linking anodal transcranial direct current stimulation (tDCS) to reductions in GABA in the primary motor cortex and motor learning (Stagg et al., 2009; Kim et al., 2014), the authors tested for changes in GABA concentration in the right cerebellar hemisphere in response to right cerebellar tDCS and attempted to link these changes to adaptation performance. There was no significant change in GABA, but exploratory analyses revealed a correlation between late adaptation and stimulation-driven GABA decrease. The authors noted as one of the reasons for the lack of GABA change in response to adaptation the long MRS acquisition time of 25 min, which might have rendered transient changes in GABAergic levels undetectable.

In a subsequent investigation of GABA changes occurring in the cerebellum during adaptation, MRS measurements were acquired in 9-min blocks from both the left and right cerebellar hemispheres (see Fig. 23.3A) while participants performed a right-hand adaptation task in the scanner (Nettekoven et al., 2022). Isolating adaptation-driven GABA changes revealed diverging GABA concentration at the right and left cerebellar nuclei (see Fig. 23.3B) with left cerebellar GABA increasing and right cerebellar GABA decreasing. The extent of the early GABA change at the right cerebellar nuclei showed a relationship with adaptation performance (Fig. 23.3C). Those participants who showed greater GABA decrease also adapted better. This relationship was specific to right cerebellar GABA change and adaptation, as there was no relationship with left cerebellar GABA change. Though these results present the first evidence for lateralized neurochemical signatures of cerebellar-dependent motor behavior of the right hand, further MRSI studies are necessary to provide a full picture of cerebellar neurochemistry and its role in motor and non-motor functions.

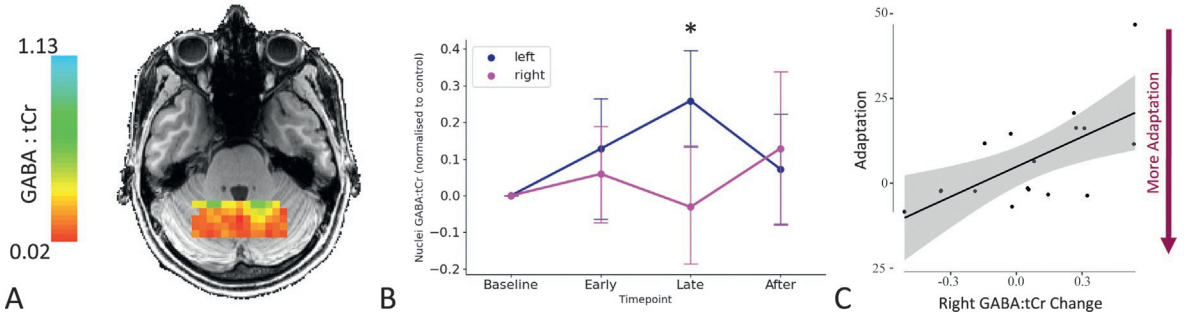


Fig. 23.3. Asymmetric neurochemical changes at cerebellar nuclei during adaptation. Magnetic resonance spectroscopic imaging (MRSI) can be used to quantify the major inhibitory neurotransmitter GABA in several cerebellar voxels in vivo, as shown for a representative participant (A). Isolating neurochemical changes in response to righthand adaptation reveals diverging GABA at the left and right cerebellar nuclei (B) and a relationship between early GABA change at the right cerebellar nuclei and adaptation performance (C). Reproduced from Nettekoven C, Mitchell L, Clarke WT, et al. (2022). Cerebellar GABA change during visuomotor adaptation relates to adaptation performance and cerebellar network connectivity: a magnetic resonance spectroscopic imaging study. J Neurosci 42: 7721–7732.

CONCLUSIONS

Asymmetries have been documented in the structure, function, and neurochemistry of the cerebellum. Functional asymmetries are largely confined to the cerebellar hemisphere contralateral to the cerebrum, while broad structural asymmetries show the same pattern in the cerebellum and cerebrum. The extent of cerebellar asymmetries has also been linked to handedness and performance on lateralized functions, such as language. However, technical challenges in measuring and analyzing cerebellar asymmetries have so far hindered thorough studies of cerebellar lateralization. Hence, several questions regarding the function and clinical consequences of cerebellar asymmetries remain open. For example, does the development of functional asymmetries in the cerebellum precede, parallel, or follow the development of corresponding cerebral functional asymmetries? To what extent does cerebellar asymmetry vary with biologic factors such as age, sex, handedness, and heredity? And what is the relationship between cerebellar asymmetry and disorders that involve the cerebellum such as schizophrenia, and how can we use this knowledge to improve diagnosis and treatment? The development of specialized imaging techniques and new tools for the study of the cerebellum now opens the opportunity to answer these questions.

References

Ackermann H (2008). Cerebellar contributions to speech production and speech perception: psycholinguistic and neurobiological perspectives. Trends Neurosci 31: 265–272.

Albus JS (1971). A theory of cerebellar function. Math Biosci 10: 25–61.

Allen G, Buxton RB, Wong EC et al. (1997). Attentional activation of the cerebellum independent of motor involvement. Science 275: 1940–1943.

Amunts K, Schlaug G, Schleicher A et al. (1996). Asymmetry in the human motor cortex and handedness. Neuroimage 4: 216–222.

Andescavage NN, Du Plessis A, McCarter R et al. (2017). Complex trajectories of brain development in the healthy human fetus. Cereb Cortex 27: 5274–5283.

Azevedo FA, Carvalho LR, Grinberg LT et al. (2009). Equal numbers of neuronal and nonneuronal cells make the human brain an isometrically scaled-up primate brain. J Comp Neurol 513: 532–541.

Bachtiar V, Stagg CJ (2013). Interindividual differences in behavior and plasticity. In: Magnetic resonance spectroscopy: tools for neuroscience research and emerging clinical applications, 243–253.

Baer LH, Park MT, Bailey JA et al. (2015). Regional cerebellar volumes are related to early musical training and finger tapping performance. Neuroimage 109: 130–139.

Bayley N (2006). Bayley scales of infant and toddler development, 3rd edHarcourt Assessment, Inc., San Antonio, TX.

Beckinghausen J, Sillitoe RV (2019). Insights into cerebellar development and connectivity. Neurosci Lett 688: 2–13.

Bernard JA, Seidler RD (2013). Relationships between regional cerebellar volume and sensorimotor and cognitive function in young and older adults. Cerebellum 12: 721–737.

Bernard JA, Leopold DR, Calhoun VD et al. (2015). Regional cerebellar volume and cognitive function from adolescence to late middle age. Hum Brain Mapp 36: 1102–1120.

Bolduc ME, Du Plessis AJ, Sullivan N et al. (2012). Regional cerebellar volumes predict functional outcome in children with cerebellar malformations. Cerebellum 11: 531–542.

Brooks JC, Faull OK, Pattinson KT et al. (2013). Physiological noise in brainstem fMRI. Front Hum Neurosci 7: 1–13.

Buckner RL, Krienen FM, Castellanos A et al. (2011). The organization of the human cerebellum estimated by intrinsic functional connectivity. J Neurophysiol 106: 2322–2345.

Busch SE, Hansel C (2023). Climbing fiber multi-innervation of mouse Purkinje dendrites with arborization common to human. Science 381: 420–427.

Cherbuin N, Reglade-Meslin C, Kumar R et al. (2010). Mild cognitive disorders are associated with different patterns of brain asymmetry than normal aging: the PATH through life study. Front Psych 1: 1–9.

Deoni SC, Catani M (2007). Visualization of the deep cerebellar nuclei using quantitative T1 and ρ magnetic resonance imaging at 3 Tesla. Neuroimage 37: 1260–1266.

Diedrichsen J (2005). Neural correlates of reach errors. J Neurosci 25: 9919–9931.

Diedrichsen J (2006). A spatially unbiased atlas template of the human cerebellum. Neuroimage 33: 127–138.

Diedrichsen J, Zotow E (2015). Surface-based display of volume-averaged cerebellar imaging data. PLoS One 10: 1–18.

Diedrichsen J, Balsters JH, Flavell J et al. (2009). A probabilistic MR atlas of the human cerebellum. Neuroimage 46: 39–46.

Diedrichsen J, Maderwald S, Kuper M et al. (2011). Imaging the deep cerebellar nuclei: a probabilistic atlas and normalization procedure. Neuroimage 54: 1786–1794.

Ding H, Qin W, Jiang T et al. (2012). Volumetric variation in subregions of the cerebellum correlates with working memory performance. Neurosci Lett 508: 47–51.

Eccles JC (1967). The cerebellum as a neuronal machine, Springer-Verlag, Berlin.

Ertekin T, Acer N, Icer S et al. (2013). Comparison of two methods for the estimation of subcortical volume and asymmetry using magnetic resonance imaging: a methodological study. Surg Radiol Anat 35: 301–309.

Fabbro F, Tavano A, Corti S et al. (2004). Long-term neuropsychological deficits after cerebellar infarctions in two young adult twins. Neuropsychologia 42: 536–545.

Fan L, Tang Y, Sun B et al. (2010). Sexual dimorphism and asymmetry in human cerebellum: an MRI-based morphometric study. Brain Res 1353: 60–73.

Fedorenko E, Hsieh PJ, Nieto-Castanon A et al. (2010). New method for fMRI investigations of language: defining ROIs functionally in individual subjects. J Neurophysiol 104: 1177–1194.

Fiez JA, Raichle ME, Balota DA et al. (1996). PET activation of posterior temporal regions during auditory word presentation and verb generation. Cereb Cortex 6: 1–10.

Fujita H, Kodama T, Du Lac S (2020). Modular output circuits of the fastigial nucleus for diverse motor and nonmotor functions of the cerebellar vermis. Elife 9: 1–36.

Glickstein M (1994). Cerebellar agenesis. Brain 117: 1209–1212.

Gocmen-Mas N, Pelin C, Canan S et al. (2009). Stereological evaluation of volumetric asymmetry in healthy human cerebellum. Surg Radiol Anat 31: 177–181.

Graydon FX, Friston KJ, Thomas CG et al. (2005). Learning-related fMRI activation associated with a rotational visuo-motor transformation. Cogn Brain Res 22: 373–383.

Haberling IS, Corballis MC (2016). Cerebellar asymmetry, cortical asymmetry and handedness: two independent networks. Laterality 21: 397–414.
Herve PY, Crivello F, Perchey G et al. (2006). Handedness and cerebral anatomical asymmetries in young adult males. Neuroimage 29: 1066–1079.
Hodge SM, Makris N, Kennedy DN et al. (2010). Cerebellum, language, and cognition in autism and specific language impairment. J Autism Dev Disord 40: 300–316.
Holland D, Chang L, Ernst TM et al. (2014). Structural growth trajectories and rates of change in the first 3 months of infant brain development. JAMA Neurol 71: 1266–1274.
Holloway RL, De La Costelareymondie MC (1982). Brain endocast asymmetry in pongids and hominids: some preliminary findings on the paleontology of cerebral dominance. Am J Phys Anthropol 58: 101–110.
Isıklar S, Demir I, Ozdemir ST et al. (2023). Examination of the development and asymmetry of the cerebellum and its lobules in individuals aged 1–18 years: a retrospective MRI study. Brain Topogr 901–925.
Ito M, Kano M (1982). Long-lasting depression of parallel fiber-Purkinje cell transmission induced by conjunctive stimulation of parallel fibers and climbing fibers in the cerebellar cortex. Neurosci Lett 33: 253–258.
Jalali R, Chowdhury A, Wilson M et al. (2018). Neural changes associated with cerebellar tDCS studied using MR spectroscopy. Exp Brain Res 236: 997–1006.
Kang X, Herron TJ, Ettlinger M et al. (2015). Hemispheric asymmetries in cortical and subcortical anatomy. Laterality 20: 658–684.
Kavaklioglu T, Guadalupe T, Zwiers M et al. (2017). Structural asymmetries of the human cerebellum in relation to cerebral cortical asymmetries and handedness. Brain Struct Funct 222: 1611–1623.
Kelly RM, Strick PL (2003). Cerebellar loops with motor cortex and prefrontal cortex of a nonhuman primate. J Neurosci 23: 8432–8444.
Kim S, Stephenson MC, Morris PG et al. (2014). TDCS induced alterations in GABA concentration within primary motor cortex predict motor learning and motor memory: a 7T magnetic resonance spectroscopy study. Neuroimage 99: 237–243.
King M, Hernandez-Castillo CR, Poldrack RA et al. (2019). Functional boundaries in the human cerebellum revealed by a multi-domain task battery. Nat Neurosci 22: 1371–1378.
Kreis R (2004). Issues of spectral quality in clinical 1H-magnetic resonance spectroscopy and a gallery of artifacts. NMR Biomed 17: 361–381.
Krienen FM, Buckner RL (2009). Segregated fronto-cerebellar circuits revealed by intrinsic functional connectivity. Cereb Cortex 19: 2485–2497.
Larsell O, Jansen J (1973). The comparative anatomy and histology of the cerebellum—review. Comp Gen Pharmacol 3: 467–468.
LeBel A, D'Mello AM (2023). A seat at the (language) table: incorporating the cerebellum into frameworks for language processing. Curr Opin Behav Sci 53: 101310.
Leggio MG, Silveri MC, Petrosini L et al. (2000). Phonological grouping is specifically affected in cerebellar patients: a verbal fluency study. J Neurol Neurosurg Psychiatry 69: 102–106.
LeMay M (1976). Morphological cerebral asymmetries of modern man, fossil man, and nonhuman primate. Ann N Y Acad Sci 280: 349–366.
Lesage E, Hansen PC, Miall RC (2017). Right lateral cerebellum represents linguistic predictability. J Neurosci 37: 6231–6241.
Li X, Crow TJ, Hopkins WD et al. (2018). Human torque is not present in chimpanzee brain. Neuroimage 165: 285–293.
Marien P, Saerens J, Nanhoe R et al. (1996). Cerebellar induced aphasia: case report of cerebellar induced prefrontal aphasic language phenomena supported by SPECT findings. J Neurol Sci 144: 34–43.
Marien P, Engelborghs S, Pickut BA et al. (2000). Aphasia following cerebellar damage: fact or fallacy? J Neurolinguistics 13: 145–171.
Marr JE (1969). A theory of cerebellar cortex. J Physiol 202: 437–470.
Marvel CL, Desmond JE (2010). Functional topography of the cerebellum in verbal working memory. Neuropsychol Res 20: 271–279.
Medina JF, Lisberger SG (2008). Links from complex spikes to local plasticity and motor learning in the cerebellum of awake-behaving monkeys. Nat Neurosci 11: 1185–1192.
Miall RC, Jenkinson EW (2005). Functional imaging of changes in cerebellar activity related to learning during a novel eye-hand tracking task. Exp Brain Res 166: 170–183.
Moberget T, Ivry RB (2016). Cerebellar contributions to motor control and language comprehension: searching for common computational principles. Ann N Y Acad Sci 1369: 154–171.
Nettekoven C, Mitchell L, Clarke WT et al. (2022). Cerebellar GABA change during visuomotor adaptation relates to adaptation performance and cerebellar network connectivity: a magnetic resonance spectroscopic imaging study. J Neurosci 42: 7721–7732.
Nettekoven C, Zhi D, Shahshahani L et al. (2024). A hierarchical atlas of the human cerebellum for functional precision mapping. Nat Commun 15: 8376. https://doi.org/10.1038/s41467-024-52371-w.
Nicolson RI, Fawcett AJ, Dean P (1995). Time estimation deficits in developmental dyslexia: evidence of cerebellar involvement. Proc Roy Soc London, Ser B Biol Sci 259: 43–47.
O'Reilly JX, Beckmann CF, Tomassini V et al. (2010). Distinct and overlapping functional zones in the cerebellum defined by resting state functional connectivity. Cereb Cortex 20: 953–965.
Olson IR, Hoffman LJ, Jobson KR et al. (2023). Little brain, little minds: the big role of the cerebellum in social development. Dev Cogn Neurosci 60: 101238.
Orts-Del'Immagine A, Pugh JR (2018). Activity-dependent plasticity of presynaptic GABAB receptors at parallel fiber synapses. Synapse.
Petersen SE, Fox PT, Posner MI et al. (1989). Positron emission tomographic studies of the processing of single words. J Cogn Neurosci 1: 153–170.
Rae C, Lee MA, Dixon RM et al. (1998). Metabolic abnormalities in developmental dyslexia detected by 1H magnetic resonance spectroscopy. Lancet 351: 1849–1852.
Raichle ME, Fiez JA, Videen TO et al. (1994). Practice-related changes in human brain functional anatomy during nonmotor learning. Cereb Cortex 4: 8–26.
Ronconi L, Casartelli L, Carna S et al. (2017). When one is enough: impaired multisensory integration in cerebellar agenesis. Cereb Cortex 27: 2041–2051.
Rosch RE, Cowell PE, Gurd JM (2018). Cerebellar asymmetry and cortical connectivity in monozygotic twins with discordant handedness. Cerebellum 17: 191–203.
Rothman DL, Petroff OA, Behar KL et al. (1993). Localized 1H NMR measurements of γ-aminobutyric acid in human brain in vivo. Proc Natl Acad Sci U S A 90: 5662–5666.
Saadon-Grosman N, Angeli PA, DiNicola LM et al. (2022). A third Somatomotor representation in the human cerebellum. J Neurophysiol 128: 1051–1073.
Saltoun K, Adolphs R, Paul LK et al. (2023). Dissociable brain structural asymmetry patterns reveal unique phenome-wide profiles. Nat Hum Behav 7: 251–268.

Schmahmann JD, Sherman JC (1998). The cerebellar cognitive affective syndrome. Brain 121: 561–579.
Schmahmann J, Doyon J, Toga A et al. (2000). MRI atlas of the human cerebellum, Elsevier.
Sereno MI, Diedrichsen J, Tachrount M et al. (2020). The human cerebellum has almost 80 of the surface area of the neocortex. Proc Natl Acad Sci U S A 117: 19538–19543.
Silveri MC, Leggio MG, Molinari M (1994). The cerebellum contributes to linguistic production: a case of agrammatic speech following a right cerebellar lesion. Neurology 44: 2047–2050.
Snyder PJ, Bilder RM, Wu H et al. (1995). Cerebellar volume asymmetries are related to handedness: a quantitative MRI study. Neuropsychologia 33: 407–419.
Stagg CJ, Best JG, Stephenson MC et al. (2009). Polarity-sensitive modulation of cortical neurotransmitters by transcranial stimulation. J Neurosci 29: 5202–5206.
Starowicz-Filip A, Prochwicz K, Klosowska J et al. (2021). Cerebellar functional lateralization from the perspective of clinical neuropsychology. Front Psychol 12: 1–12.
Stipdonk LW, Boumeester M, Pieterman KJ et al. (2021). Cerebellar volumes and language functions in school-aged children born very preterm. Pediatr Res 90: 853–860.
Stoodley CJ (2014). Distinct regions of the cerebellum show gray matter decreases in autism, ADHD, and developmental dyslexia. Front Syst Neurosci 8: 1–17.
Stoodley CJ, Schmahmann JD (2009). Functional topography in the human cerebellum: a meta-analysis of neuroimaging studies. Neuroimage 44: 489–501.
Stoodley CJ, MacMore JP, Makris N et al. (2016). Location of lesion determines motor vs. cognitive consequences in patients with cerebellar stroke. NeuroImage Clin 12: 765–775.
Szeszko PR, Gunning-Dixon F, Ashtari M et al. (2003). Reversed cerebellar asymmetry in men with first-episode schizophrenia. Biol Psychiatry 53: 450–459.
Thomas Yeo BT, Krienen FM, Sepulcre J et al. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. J Neurophysiol 106: 1125–1165.
Tomasch J (1969). The numerical capacity of the human corticopontocerebellar system. Brain Res 13: 476–484.
Van Overwalle F, D'aes T, Marien P (2015). Social cognition and the cerebellum: a meta-analytic connectivity analysis. Hum Brain Mapp 36: 5137–5154.
Vassar R, Schadl K, Cahill-Rowley K et al. (2020). Neonatal brain microstructure and machine-learning-based prediction of early language development in children born very preterm. Pediatr Neurol 108: 86–92.
Wang D, Buckner RL, Liu H (2013). Cerebellar asymmetry and its relation to cerebral asymmetry estimated by intrinsic functional connectivity. J Neurophysiol 109: 46–57.
Wang D, Buckner RL, Liu H et al. (2014). Functional specialization in the human brain estimated by intrinsic hemispheric interaction. J Neurosci 34: 12341–12352.
Yan X, Kong R, Xue A et al. (2023). Homotopic local-global parcellation of the human cerebral cortex from resting-state functional connectivity. Neuroimage 273: 120010. https://doi.org/10.1016/j.neuroimage.2023.120010 Epub 2023 Mar 12, PMID: 36918136; PMCID: PMC10212507.
Zhang Y, Wu X (2021). Asymmetries of cerebellar lobe in the genus homo. Symmetry 13.
Zhi D, Shahshahani L, Nettekoven C et al. (2025). A hierarchical Bayesian brain parcellation framework for fusion of functional imaging datasets. Imaging Neurosci 3. https://doi.org/10.1162/imag_a_00408.

Index

NB: Page numbers in *italics* refer to figures and tables.

A

Aachener Aphasia Test (AAT) 73–74
Acalculia 461–462
Acquired prosopagnosia 437
Aging 356–358, *357*
Alexias 303–305
  attentional alexia 303
  central alexias 304–305
  deep alexia 305
  hemianopic alexia 303
  left hemi-alexia 303
  letter position alexia 303
  neglect alexia 303–304, *305*
  peripheral alexias 303–304
  phonologic alexia 305
  pure alexia 303, *305*
  right hemi-alexia 303, *304*
  surface alexia 305
Alien-hand syndrome 157–158, 162–163, 398–399
Allocentric error 303–304
Allometry 235–236
Alzheimer disease (AD) 101–104, *103*, 411
American Sign Language (ASL) 330, 332, 334–336, 338–342
Amphibians 213, 219–220
Amyotrophic lateral sclerosis (ALS) 106–107
Analogic magnitude representation 465
Anatomic asymmetry *16*
  accumbofrontal tract 28
  anterior commissure 21
  arcuate fasciculus 24–25
  cingulum 25
  corpus callosum 20–21
  cortico-spinal tract (CST) 26–27
  fornix 26
  frontal aslant tract (FAT) 25
  frontal longitudinal system (FSL) 29
  fronto-insular tracts (FITs) 28
  fronto-parietal U-shaped tracts 31
  fronto-striatal projections 28
  inferior fronto-occipital fasciculus (IFOF) 23
  inferior longitudinal fasciculus (ILF) 23
  medial occipital longitudinal tract (MOLT) 24
  middle longitudinal fasciculus (MdLF) 24
  optic radiation 27
  superior longitudinal fasciculus (SLF) 24
  thalamic radiations 28
  uncinate fasciculus 23
  vertical occipital fasciculus (VOF) 26
Angular gyrus (AG) 466
Anosognosia 130
Anterior temporal lobes (ATL) atrophy 428
Anticipatory motor planning 189
Aphasia 105–106, 141–144, 272
  hemispheric specialization of language (HSL) 358–359, *358*
  sign language 334–335
Apperception 484–485
Apperceptive agnosia 486
Approximate number system (ANS) 465
Art
  colors 412–413
  creativity 414
  drawing 412
  early dominant model 409–410
  evolutionary background 414–415
  hemispheric asymmetries 414
  imagination and imagery 414
Artificial grammar 274
Aspontaneous movements 188
Associative agnosia 486
Attentional alexia 303
Attentional bias 306
Attention deficit hyperactivity disorders (ADHD) 115–116
Atypical brain asymmetry
  in human visceral situs anomalies 53–58
    systematic literature 53–58
  situs inversus
    brain functional asymmetry 55
    handedness 53–55, *54*
Atypical functional segregation 51–52
Automatic-voluntary dissociation 394
Awake surgery 65–66, 68–73, 78, 80–81

B

Behavioral inattention test (BIT) 120
Bias connectivity hypothesis 309
Bihemispheric neurostimulation 175
Biopsychosocial approach 259–260
Birds 214–215, 220
Blood oxygen level dependent (BOLD) response 340
Boston Naming Test (BNT) 74
Braille reading, in congenitally blind 313–314, *314*
Brain asymmetries 50–53, 242, 271–272
  brain functional segregation 51
    atypical functional segregation 51–52
    reversed typical functional segregation 51
  and endocranial morphology *233*, 234–235
  in fossil hominids 235–237, *235–236*
  functional hemispheric language dominance 250
  genome-wide association studies 242–245, *244*
  latent dimensions 37–38, *39*
Brain asymmetries *(Continued)*
  neurocognitive system left-right asymmetry 50–52
  ontogenesis 52
    central nervous system asymmetric development 52
    neurulation 52
  reproducibility 204, *205–206*
  rigor 204, *205–206*
  shared genetic effects 248–249, *249*
  statistical power 204, *205–206*
Brain functional segregation 51
  atypical functional segregation 51–52
  reversed typical functional segregation 51
BrainMap database 338
Brains and endocasts 233–234, *233*
Brain torque 41–42, 50, 55–58
Brain tumors, language-relevant
  cognitive difference 67–68
  cortical and subcortical area functions 78, *79–80*
  functional connectivity alterations 77–78
  gliomas (*see* Gliomas)
  language system affecting identification method
    invasive techniques 71–73, *72–73*
    noninvasive functional technique 68–71, *69–70*
    noninvasive structural technique 68–71, *69–70*
  lobar differences 68
  meningiomas (*see* Meningiomas)
  patients, language and cognitive profiles 73–76
    gliomas 73–75
    meningiomas 75–76
    mild aphasia 73–74, *74*
    spontaneous speech 76
    supplementary motor area (SMA) syndrome 76
  sex differences 67–68, *67*
  types 65–66
  white matter dysfunctions 76–77, *77*
British Sign Language (BSL) 332–334, 339–340
Broca's rule 40

C

CA. *See* Constructional apraxia (CA)
Callosal apraxia 157–158, 396–397
Callosotomy 155–156
  behavioral outcome 157–162, *160*
  clinical perspectives 157–158
  corpus 156–157
Central alexias 304–305

Central nervous system, asymmetric development of 52
Cerebellar asymmetries
  functional lateralization 372–374, *373*
    resting-state connectivity asymmetries 373–374
    task-based asymmetries 372–373
    technical considerations 374
  structural asymmetries 372
    broad cerebellar structure 369–371
    cytoarchitecture 371–372
    deep cerebellar nuclei 371
Cerebellar Cognitive Affective Syndrome 371
Cerebral palsy, cognitive developmental consequences of 189–190
Chirality 247–250
Ciliopathy 50, 53–55
Classifiers 332
Cognitive asymmetries 218–222
  amphibians 219–220
  birds 220
  fish 218–219
  invertebrates 221–222
  mammals 221
  reptiles 220
Cognitive functions 186–187
Cognitive neuropsychology 462
Color agnosia 412–413
Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH) model 174
Conceptual thinking capability 415
Congenital aphantasia 492
Congenital prosopagnosia (CP) 438
Congruent stimuli 482, *482*
Conscious attention 122
Constructional apraxia (CA)
  clinical assessment 400
  clinical manifestations 399–400
  hemispheric asymmetries 400–402
Corpus callosotomy 156–157
Corpus callosum 117, 121, 155–158, 162–163
  riddle 8–9
  Roger Sperry 8–9
Cortical attention centers 117–118, *118*
Cortical localization 2–3
Cortico-basal syndrome 106, *107*
Craniovascular traits 237
Creativity 414
Crossed aphasia 141–144
Crossed-uncrossed difference (CUD) 121
Cytoarchitectonic probability 16, *17*
Cytoarchitectural asymmetries 17–18

D

Declarative memory 449
Deep alexia 305
Deep cerebellar nuclei 371
Default-executive coupling hypothesis of aging (DECHA) model 356, *357*
Default mode network (DMN) 356
Developmental prosopagnosia 438
Diffusion spectrum imaging (DSI) 21
Diffusion tensor imaging (DTI)
  schizophrenia 93
  sign language 341
Diffusion-weighted imaging (DWI) 18, 28
Direct cortical electrostimulation (DCE) 464–465
Directional scanning effect 306
Disconnection syndrome 158, 162–163
Divided Visual Field Paradigm 116
Dorsal attention network (DAN) 117–118
Drawing 412

E

Edinburgh Handedness Inventory (EHI) 380–381
Egocentric error 303–304
Egocentric neglect 130
Emotions 122
  cognitive system 422–423, *422*
  hierarchical models 422–423
  lateralization
    animals 425–426
    autonomic components 424
    clinical observations 423
    communicative aspects 423–424
    experimental studies 423–424
    hemispheric asymmetries 425–426
    neuroimaging studies 424
    nonhuman primates 426–427
  nature 422–423
Endocasts 233–234, *233*
Endocranial morphology *233*, 234–235
Event-related potentials (ERPs) 335–337, *336*, 482–483
  logographic reading 311

F

Figurative language 289, 295, *296*
  definition 38–41
  figures of speech *290*
    definition 289–291
    idioms 290–291
    irony 290
    metaphors 289–290
    metonymy 290
    proverb 291
    sarcasm 290
    simile 290
  metaphors 38–40
  neural correlates
    of idioms 292–293
    of irony 294–295
    of metaphor 293–294
  right-hemisphere hypothesis 291–292
Finite-state grammars 274
Fish 218–219
Forced handedness retraining 387
Fossil hominids, brain asymmetries in 235–237, *235–236*
Fossil species 237–238
Frequency hypothesis 184
Frontal variant AD (Fv-AD) 104
Frontoparietal network (FPN) 356
Frontotemporal dementia-amyotrophic lateral sclerosis (FTLD-ALS) spectrum
  amyotrophic lateral sclerosis (ALS) 106–107
  behavioral variant 106
  cortico-basal syndrome 106, *107*
  primary progressive aphasia nonfluent/agrammatic variant 105–106
  progressive supranuclear palsy 106, *107*
  semantic variants 104–105
Functional cerebral asymmetries (FCAs)
  sex/gender differences 256–257
Functional craniology 233
Functional language network 272–275, *273*
Functional lateralization 38–41
  cerebellar asymmetries 372–374, *373*
    resting-state connectivity asymmetries 373–374
    task-based asymmetries 372–373
    technical considerations 374
  handedness 38, 40–41
  language 40–41
  language development 276–279, *277*, *279*
  language lateralization 38–40, *40*
  network analysis 41
  vs. structural asymmetry 42–43
Functional magnetic resonance imaging (fMRI) 372–373, 411–412, 414, 481–482
  hemispheric specialization of language (HSL) 352
  sign language 337–340
Functional near-infrared spectroscopy (fNIRS) 466
Functional transcranial Doppler sonography (fTCD) 38–39, 333–334
Fusiform Imagery Node (FIN) 490, *491*

G

γ-aminobutyric acid (GABA) 375, *375*
Gene-brain-handedness associations 245–247, *246*
Gene expression 242, 247, 249
Gene-set enrichment analysis 243
Genome-wide association studies
  of brain structural asymmetry 242–245, *244*
  of handedness 245
German Sign Language (DGS) 328–329, *329*, 331–332
Gestural communication 198–199, *199*, *200*
Gliomas 65–66, 73–75
  cortical and subcortical area functions 78, *79–80*
  patients, language and cognitive profiles 73–75
  prognosis 66
  surgery effect 78–81
Global perception 484

H

Handedness
  assessment 380–382
  best practice 382–383
  brain region dissociation 206–207
  categories
    hand preference 383
    hand skill 383–384
  cerebellar structural asymmetry 370
  cerebellum 385
  cognitive abilities 386
  cognitive functions development 186–187
    language 186–187
    tool use 187
  development
    hand-use preferences 183
    historical approach 182–183, 185–186
    intentional stance approach 182–183
    perinatal brain insult 188–189
  functional lateralization 40–41

Handedness *(Continued)*
genome-wide association studies 245
individual variation 204–206
motor asymmetries 384
in nonhuman primates 197–200, *199*
chimpanzee *198*
gestural communication 198–199, *199*, *200*
tool use 199–200, *200*
phylogenetic variation 204–206
reproducibility 204, *205–206*
retraining 386–387
rigor 204, *205–206*
in situs inversus 53–55, *54*
spinal cord 385–386
statistical power 204, *205–206*
Hand preference 380–381
Hand skill 381–382
Handwriting speed test *382*
hangul 310–311
Hemianopic alexia 303
Hemispatial neglect 116–117, *117*
Hemispatial theory 116
Hemisphere dominance 170
Hemispheric asymmetries 101–102, 104, 233
benefits 170–171
neurodegenerative diseases
Alzheimer disease (AD) 101–104, *103*
amyotrophic lateral sclerosis (ALS) 106–107
aphasia 105–106
cortico-basal syndrome 106, *107*
lewy body disease (LBD) 107–108
Parkinson disease (PD) 107–108
progressive supranuclear palsy 106, *107*
sex/gender differences 256–257
biopsychosocial approach 259–260
clinical implications 260–261
contemporary views 257–259
socioeconomic status (SES) 175–176
Hemispheric asymmetry reduction in older adults (HAROLD) model 172, 356, *357*
Hemispheric encoding retrieval asymmetry (HERA) model 161, 454, 456–457
Hemispheric lateralization
development 182
Hemispheric specialization 183–184, 197–199, 205–206
infant hand preferences 184–185
Hemispheric specialization of language (HSL) 352, 360
arcuate fasciculus (ARC) 355
corpus callosum (CC) 355
diffusion tensor imaging (DTI) 355
neuroimaging 352, *353*
neuroplasticity 356–360
reorganization
in healthy aging 356–358, *357*
in poststroke aphasia 358–359, *358*
in temporal lobe epilepsy (TLE) 359–360
resting-state fMRI (rs-fMRI) 354, 358–359
through anatomic connectivity 355–356
through anatomic cortical thickness 354–355
through functional brain connectivity 354
through functional brain mapping 352–354, *353*
voxel-based morphometry-MRI (VBM-MRI) 354–355
Hemispheric specializations 155, 161, 164
Heterotaxy 48–49
Hierarchical perception 482, *482*
History, cerebral asymmetry 1–2
before Broca 2–3
Broca and cancel culture 3–4
cortical localization 2–3
Home Handedness Questionnaire (HHQ) 381
Homo sapiens 231, 235, 237–238
Horizontal intraparietal sulcus (hIPS) 465
HSL. *See* Hemispheric specialization of language (HSL)
Human evolution 238
Hyperschematia 412

I

Ideational apraxia 394
Ideomotor apraxia 394
Idioms 290–293
Imagination 414
Imitation 395
Incongruent stimuli 482, *482*
Inferior frontal gyrus (IFG) 203–204, *203*
Intentional stance 189
Interhemispheric transfer time (ITT) 121
Interindividual variability
accumbofrontal tract 28
anterior commissure 21
arcuate fasciculus 25
cingulum 25
corpus callosum 21
cortico-spinal tract (CST) 27
fornix 26
frontal aslant tract (FAT) 25
frontal longitudinal system (FSL) 29
fronto-insular tracts (FITs) 28
fronto-parietal U-shaped tracts 31
fronto-striatal projections 28
inferior fronto-occipital fasciculus (IFOF) 23
medial occipital longitudinal tract (MOLT) 24
middle longitudinal fasciculus (MdLF) 24
optic radiation 27
superior longitudinal fasciculus (SLF) 24
thalamic radiations 28
uncinate fasciculus 23
vertical occipital fasciculus (VOF) 26
Intransitive gestures 397
Intraparietal sulci (IPS) 465, 467
Invertebrates 216–217, 221–222
Irony 290, 294–295
Isomerisms 49

K

kana script 310–313, *311*
kanji script 310–313, *311*
Kartagener syndrome 49

L

Language 270–271, 327–330
left-lateralization 282
linguistic signals and representations 270, *270*
neurobiology 271
Language network 339–342, *341*
development 276–281
functional 272–275, *273*
structural 275–276
Language processing
development
functional lateralization 276–279, *277*, *279*
with one hemisphere 280–281
structural lateralization 279–280, *280*
language network
development 276–281
functional 272–275, *273*
structural 275–276
lateralization 271–272, *272*
near-infrared spectroscopy (NIRS) 278
Language use, modality of 333–334, 342–345
LARA model 357–358, *357*
Lateralization
of brain function 170
language processing 271–272, *272*
neglect
in brain damaged animals 128–129
in brain-damaged children 129
in reading (*see* Reading, lateralization)
sign language 328, 333–338, 342–343
Lateralization quotient (LQ) 380–381
Lateralized spontaneous motor behavior 212–217
amphibians 213
birds 214–215
invertebrates 216–217
mammals 215–216
reptiles 213–214
Lateral occipital complex (LOC) 481–482
Left hemi-alexia 303
Left–right axis formation, microtubules 247–248
Letter position alexia 303
Lewy body disease (LBD) 107–108
Lexicalization errors 305
Limb apraxia (LA). *See* Upper limb apraxia
Limb asymmetry 212–217
amphibians 213
birds 214–215
invertebrates 216–217
mammals 215–216
reptiles 213–214
Limb-kinetic apraxia 394
Line bisection 131–132
Lip-reading 315, *316*
Literary arts 413
Locus coeruleus (LC) 115–116
Logographic reading
vs. alphabetic script 310–313, *311*
event-related potentials 311
functional neuroimaging 311–312
neuropsychologic studies 312–313, *313*
tachistoscopic studies 311

M

Madame D 489–490, *490*
Magnetic resonance imaging, sign language 337–340
Magnetic resonance spectroscopic imaging (MRSI) 375, *375*
Magnetic resonance spectroscopy (MRS) 374–375
Magnetoencephalography (MEG) 466
Mammals 215–216, 221
Many-to-many hypothesis 309
Marr-Albus-Ito model 371–372
Material-specific hypothesis 454–456
Meaningless gestures 397–398

Medial temporal lobe epilepsy 454–456
Meningiomas 65–66
  language and cognitive profiles 75–76
  patients, cortical and subcortical area functions 78
  surgery effect 81
Metaphors 289–290, 293–294
Metonymy 290
Microtubule-associated protein (MAPT) 245–246, 248
Microtubules, in left–right axis formation 247–248
Mild aphasia 73–74, *74*
Mind-blindness 484–485
Mirror movements 188–189
Modality-specific information 456
Motor apraxia 394
Mouth gestures 330–331
Multiplication errors 465
Multireceptor approach 17–18
Multivariate genome-wide association testing 243
Musical arts 413–414
Music reading 315–316, *317*

N

N-acetylaspartate (NAA) 375
Neglect
  defective manifestations 130
  etiology 128
  in hemispheric differences 141, *142–143*
  history 128
  lateralization
    in brain damaged animals 128–129
    in brain-damaged children 129
  as multicomponent syndrome 129–131
  productive manifestations 130
  right and left-side 141–144
    asymmetric sensory stimulations 144
    caloric vestibular stimulation 144
    prism adaptation 144
  spatial neglect (*see* Spatial neglect)
  types 128
Neglect alexia 303–304, *305*
Neglect dyslexia 130
Network analysis
  functional lateralization 41
  structural asymmetry 42
Neural correlates
  of idioms 292–293
  of irony 294–295
  of metaphor 293–294
Neuroanatomic asymmetries
  and behavioral correlates 200–204, *201–202*
  inferior frontal gyrus (IFG) 203–204, *203*
Neurochemical asymmetries 374–375
Neurocognitive aging
  asymmetry reduction 172–173
    cognitive processing 172–173
    hand dominance 173
    motor performance 173
  bihemispheric recruitment 174
  compensatory overactivation 174
  dedifferentiation 173–174
Neurocognitive aging *(Continued)*
  right hemisphere
    aging hypothesis 171–172
    and cognitive reserve 174–175
  theories 170–171
Neurocognitive system, left–right asymmetry 50–52
Neurodegenerative diseases
  hemispheric asymmetry
    Alzheimer disease (AD) 101–104, *103*
    amyotrophic lateral sclerosis (ALS) 106–107
    aphasia 105–106
    cortico-basal syndrome 106, *107*
    Lewy Body Disease (LBD) 107–108
    Parkinson disease (PD) 107–108
    progressive supranuclear palsy 106, *107*
Neurodevelopment 248–249
Neuroimaging studies 370–373, 482–483
Neurology
  antilocalizationist tendencies 5–6
  coalescence 6–7
  Lashley 6–7
Neuronal recycling hypothesis 309
Nondeclarative memory 449
Number form area (NFA) 465–466
Numbers reading 316

O

Ontogenesis 52
Optic aphasia 486–488

P

Paleoanthropology 232–233
Paleoneurobiology 233
Paleoneurology, limitation of 234
Pantomiming 395
Parkinson disease (PD) 107–108
Pars opercularis 249
Pegboard tests 382
Perceptual neglect 130
Peripheral alexias 303–304
Petalias 235
Phonologic alexia 305
Phrase-structure grammars 274
Planum temporale 242
Positron emission tomography (PET) 372, 482–483
Posterior–anterior shift in aging (PASA) model 356, *357*
Prefrontal cortex 292
Primary acalculia 462
Primary ciliary dyskinesia (PCD) 49
Primates 206–207
Progressive supranuclear palsy 106, *107*
Proverb 291
Pseudoneglect effect 119–120
Psychiatric traits, shared genetic effects 248–249, *249*
Psychology
  antilocalizationist tendencies 5–6
  coalescence 6–7
  Lashley 6–7
Psychotic disorders 260
Pure alexia 302–303, *302*, *305*
Pyramids and Palm Tree Test (PPTT) 72–73

R

Radionuclide imaging 337–340, *337*, *339*
Reading, lateralization 302
  Braille reading, in congenitally blind 313–314, *314*
  logographic reading
    vs. alphabetic script 310–313, *311*
    event-related potentials 311
    functional neuroimaging 311–312
    neuropsychologic studies 312–313, *313*
    tachistoscopic studies 311
  musical notation 315–316, *317*
  in neuroimaging 306–307, *307*
  nonvisual text 313–314, *314*
  in reading development 308–310
    developmental dyslexia 308–309, *310*
    developmental hypotheses 308–309
  reading numbers 316
  structural schematic 316–317, *317*
  visual non-text reading 314–315
Regularization errors 305
Reptiles 213–214, 220
Resting-state fMRI (rs-fMRI), hemispheric specialization of language (HSL) 354, 358–359
Reversed typical functional segregation 51
Right-frontal left-occipital volumetric dominance 236
Right hemi-alexia 303, *304*
Right hemisphere 307–308
  aging hypothesis 171–172
  and cognitive reserve 174–175
  dominance 170
Right-hemisphere face superiority 439–440
Right-hemisphere hypothesis 291–292
Role-differentiated bimanual manipulation (RDBM) 183, 186

S

Sarcasm 290
Schizophrenia 90–96
  air encephalographic studies 91
  cerebral asymmetry 90–91
  CT scan 91
  diffusion tensor imaging (DTI) 93
  electroencephalography (EEG) 93
  functional brain asymmetry 91–93
  language asymmetry
    disrupted asymmetry 95
    and genetic load 94
    historical framework 94
    symptoms 95–96
  language disturbances 94
  magnetic resonance imaging (MRI)
    cortical areas 92
    subcortical structures 92–93
    white matter 93
  postmortem studies 91–92
  structural brain asymmetry 91–93
Secondary acalculia 462
Sectional asymmetries 16–17
Semantic information 456
Semantic memory 449–451, 456–457
Semantic reading error 305
Sensorimotor feedback loops 184
Sentence processing 273–274, 277–278

Sex differences 256–257
  brain tumors 67, *67*
Sex/gender differences
  functional cerebral asymmetries (FCAs) 256–257
    from early behavioral studies 256–257
    from functional neuroimaging 257
  in hemispheric asymmetries 256–257
    biopsychosocial approach 259–260
    clinical implications 260–261
    contemporary views 257–259
  in recovery 260
  structural cerebral asymmetries 256
Sex hormones 257–261
Shape hypothesis 309
Sign blindness 334
Sign language 327–328
  acquisition 332–334
  aphasia 334–335
  in deaf 314–315
  development 332–334
  functional neuroanatomy 343–344, *344*
  functional neuroimaging 335–340
    event-related potentials (ERPs) 335–337, *336*
    magnetic resonance imaging 337–340
    radionuclide imaging 337–340, *337*, *339*
  left-lateralization 328, 337–338, 342–343
  lexical and syntactic development 332, *333*
  linguistic analysis 330–332, *331*
  meta-analysis 337–339, *337*
  neural basis 343, *344*
  structural neuroimaging 340–342, *341*
Simile 290
Simon effect 120
Situs inversus 48, 247–248
  brain functional asymmetry 55, *56*
  brain structural asymmetry 55–58, *57*
  handedness in 53–55, *54*
Situs inversus totalis (SIT) 48, 53
Social cognition 105–106, 108
Spatial acalculia 461–462
Spatial hemineglect 119
Spatial neglect
  assessment 131–133
    activities of daily living (ADL) 132
    information technology (IT) 132–133
    near extra-personal space 131–132, *131–133*
    peri-personal space 131–132, *131–133*
    personal space 132
    test batteries 132
  external space 130
  internal space 130
  left *vs.* right (*see* Spatial neglect, left *vs.* right)
Spatial neglect, left *vs.* right
  anatomo-functional correlates
    extra-personal neglect 137–139
    personal neglect 139
  behavioral similarities and differences 134–137
    anosognosia 136–137
    contralateral extinction 136
    dyscalculia 136
    dysgraphia 136
    dyslexia 136
    extra-personal neglect 134–135
Spatial neglect, left *vs.* right *(Continued)*
    input *vs.* output neural systems 135
    reference frames 135–136
    representational neglect 135
    somatoparaphrenia 137
Spatial numerical association of response codes (SNARC) 466
Speech production, lateralization in meta-analyses 271–272, *272*
Split-brain
  riddle 8–9
Split-brain patients 117
  callosotomy 155–156
    behavioral outcome 157–162
    clinical perspectives 157–158
    corpus 156–157, 162–163
  disconnection effect 156–157
Split-brain studies 306
Spontaneous movements 188
Spontaneous speech 76
Stroop task 122–123
Structural asymmetries 41–42, 269
  brain torque 41–42
    global asymmetries beyond 42
  functional lateralization *vs.* 42–43
  network analysis 42
Structural cerebral asymmetries, sex/gender differences 256
Structural language network 275–276
Structural lateralization, language development 279–280, *280*
Subcortical asymmetries 17
Subcortical attention centers 118–119
Substitution errors 465
Superior longitudinal fasciculus (SLF) 118, *118*
Supplementary motor area (SMA) syndrome 76, 398–399
Surface alexia 305
Surface asymmetries 16–17
Syntax 271–272, 275, 278, 282

T

Tapley and Bryden dot-filling task 382
Temporal lobe 295
Temporal lobe epilepsy (TLE) 356, 359–360, 454–456
Tractography 18, 21–23, 25–29, 68–73, *69*, 77
Transcranial direct current stimulation (tDCS) 439–440, 467–470
Transcranial magnetic stimulation (TMS) 439–440, 467–470
Transitive gestures 397
Triple code model (TCM) 465–466

U

Unconscious attention 122
Unilateral cerebellar lesions 121
Unilateral extinction 117
Unilateral spatial neglect (ULN) 104
Unilateral spatial neglect, in humans 127–128
Upper limb apraxia
  clinical assessment 395
  clinical manifestations 393–395
  hemispheric asymmetries 395–399
U-shaped tracts 18, 28–31
  fronto-parietal U-shaped tracts 29–31, *30*
  occipital U-shaped tracts 29, *30*
  parietal U-shaped tracts 29, *30*
  short frontal tracts 28–29
    frontal longitudinal system (FSL) 28–29
    fronto-insular tracts (FIT 1-5) 28
    fronto marginal tract (FMT) 29
    fronto-orbito-polar (FOP) 29, *29*

V

Ventral attention network (VAN) 117–118
Ventral temporal cortex (VTC) 481, 489, 491–493
Verbal word frame 466
Visceral asymmetry
  anomalies, cause of 49
  and brain development 52–53
  ontogenesis 49–50
    lateral plate mesoderm 50
    motile cilia 49–50
    organ primordia 50
  phenotypes 47–49, *48*
    heterotaxy 48–49
    situs inversus 48
Visceral laterality 246–248
Visual Arabic form 465
Visual art 411
Visual mental imagery 490–492
Visual object recognition 481–490
Visual Object Space Perception battery (VOSP) 485–486
Visual word form area (VWFA) 303, 306–309, 313–315, 465–466
Visuospatial attention
  brain-damaged patients
    hemispatial neglect 116–117, *117*
    unilateral extinction 117
  brain-imaging
    cortical centers 117–118, *118*
    subcortical attention centers 118–119
    superior longitudinal fasciculus (SLF) 118, *118*
  and category-specific cortical areas 121–122
  hemispheric differences
    emotion 122
    in unconscious *vs.* conscious attention 122
  interhemispheric differences
    alerting 115–116
    executive functions 122–123
    orienting 116–122
  interhemispheric transfer time (ITT) 121
  left hemisphere (LH) 119–121, *119*
    left and right angular gyrus 120
    multitasking 120
    Simon effect 120
    visuospatial bias 120
    in visuospatial memory 120
  unilateral cerebellar lesions 121
Visuospatial bias 120
Voluntary handedness retraining 387
Voxel-based lesion-symptom mapping 485–486
Voxel-based morphometry-MRI (VBM-MRI)
  hemispheric specialization of language (HSL) 354–355

W

Wada test 334
Waterloo Footedness Questionnaire (WFQ) 384
WatHand Box Test (WBT) 381
WatHand Cabinet Test (WHCT) 381
White matter connectional asymmetries 18–31
  association pathways 18, 21–26, *22*
    arcuate fasciculus 24–25
    cingulum 25
    frontal aslant tract 25
    inferior fronto-occipital fasciculus 22–23
    inferior longitudinal fasciculus (ILF) 23
    medial occipital longitudinal tract (MOLT) 24
    middle longitudinal fasciculus (MdLF) 24
    superior longitudinal fasciculi (SLF I-III) 23–24
    uncinate fasciculus 23
    vertical occipital fasciculus (VOF) 25–26
    vertical systems 25–26
  commissural pathways 18, 20–21
    anterior commissure *20*, 21
    corpus callosum 20–21, *20*
  connectional variability 19–20, *19*
  projection pathways 18, 26–28, *27*
    accumbofrontal tract 28
    cortico-spinal tract (CST) 26–27
    fornix 26
    fronto-pontine tract 28
    fronto-striatal projections 28
    optic radiation 27
    thalamic radiations 27–28
  U-shaped tracts (*see* U-shaped tracts)
White matter dysfunctions 76–77, *77*
White matter, schizophrenia 93
Working memory 450–452

elsevier.com/books-and-journals