Histology-Based Average Template of the Marmoset Cortex With Probabilistic Localization of Cytoarchitectural Areas

Piotr Majka, Sylwia Bednarek, Jonathan M. Chan, Natalia Jermakow, Cirong Liu,
Gabriela Saworska, Katrina H. Worthy, Afonso C. Silva, Daniel K. Wójcik, Marcello G.P. Rosa

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Template files

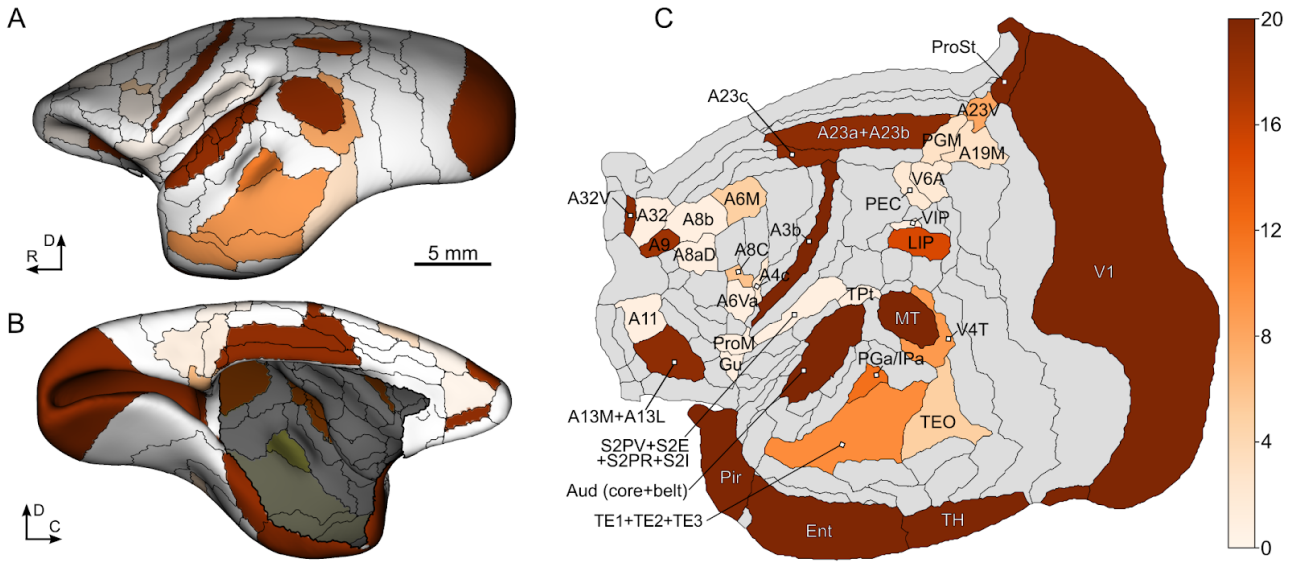


Figure S1: Summary of the label maps delineated in experimental cases to improve the accuracy of registration-based segmentation of each reconstruction. **A**, **B**: Medial and lateral views of the mid-thickness surface illustrating how many times, for the entire process of mapping all 20 reconstructions, individual cytoarchitectural areas were used to guide the registration process. **C**: Unfolded reconstruction of the cortex (left hemisphere representation; rostral to the left, medial to the top) presenting the same information. Note that eight label maps were drawn in each hemisphere: area 3b (A3b), auditory core and belt, Entorhinal cortex (Ent), Piriform cortex (Pir), prostriate area (ProS), temporal area TH, primary visual cortex (V1), middle temporal visual area (MT). Detailed information on areas outlined in each hemisphere is provided in Table S1.

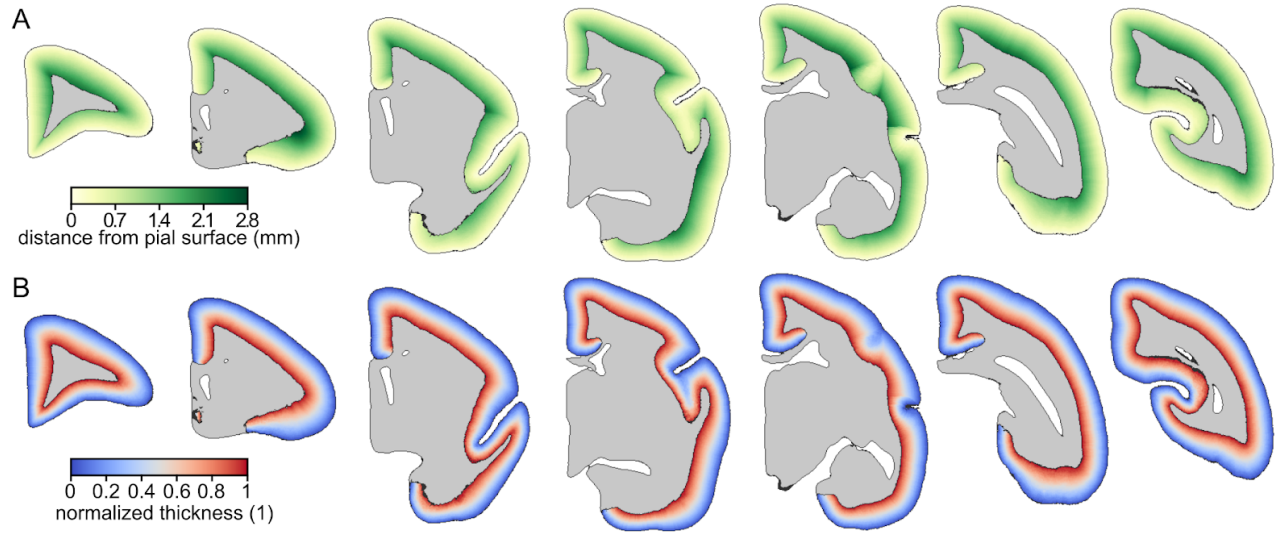


Figure S2: Continuation of Fig. 4; Coronal cross-sections at various anterior-posterior levels illustrating additional data layers provided with the template. **A**: Depth below the pial surface. **B**: Normalized thickness map (zero corresponds to the pial surface, one to the border between gray and white matter). All datasets are available for download from http://www.marmosetbrain.org/nencki_monash_template.

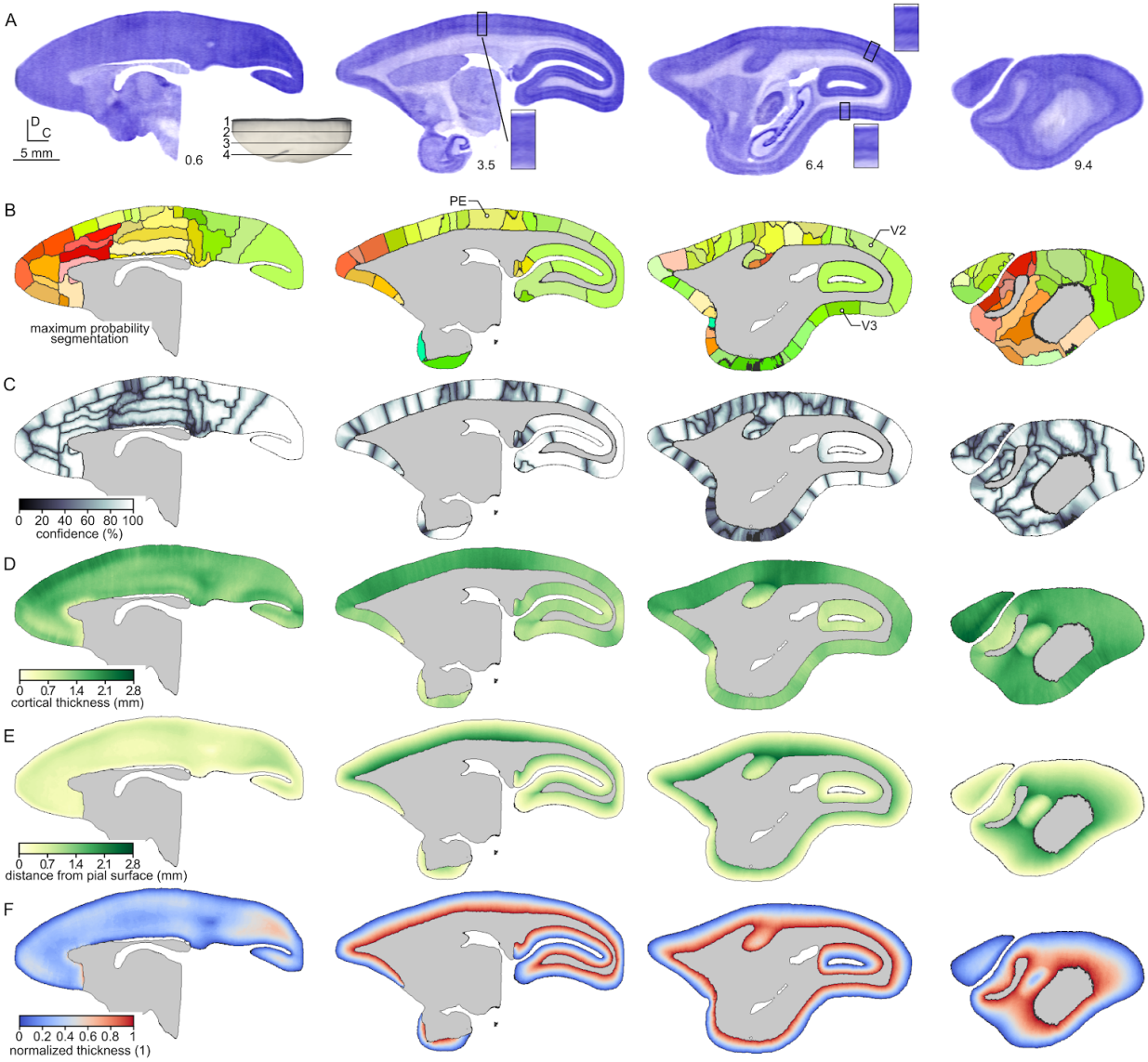
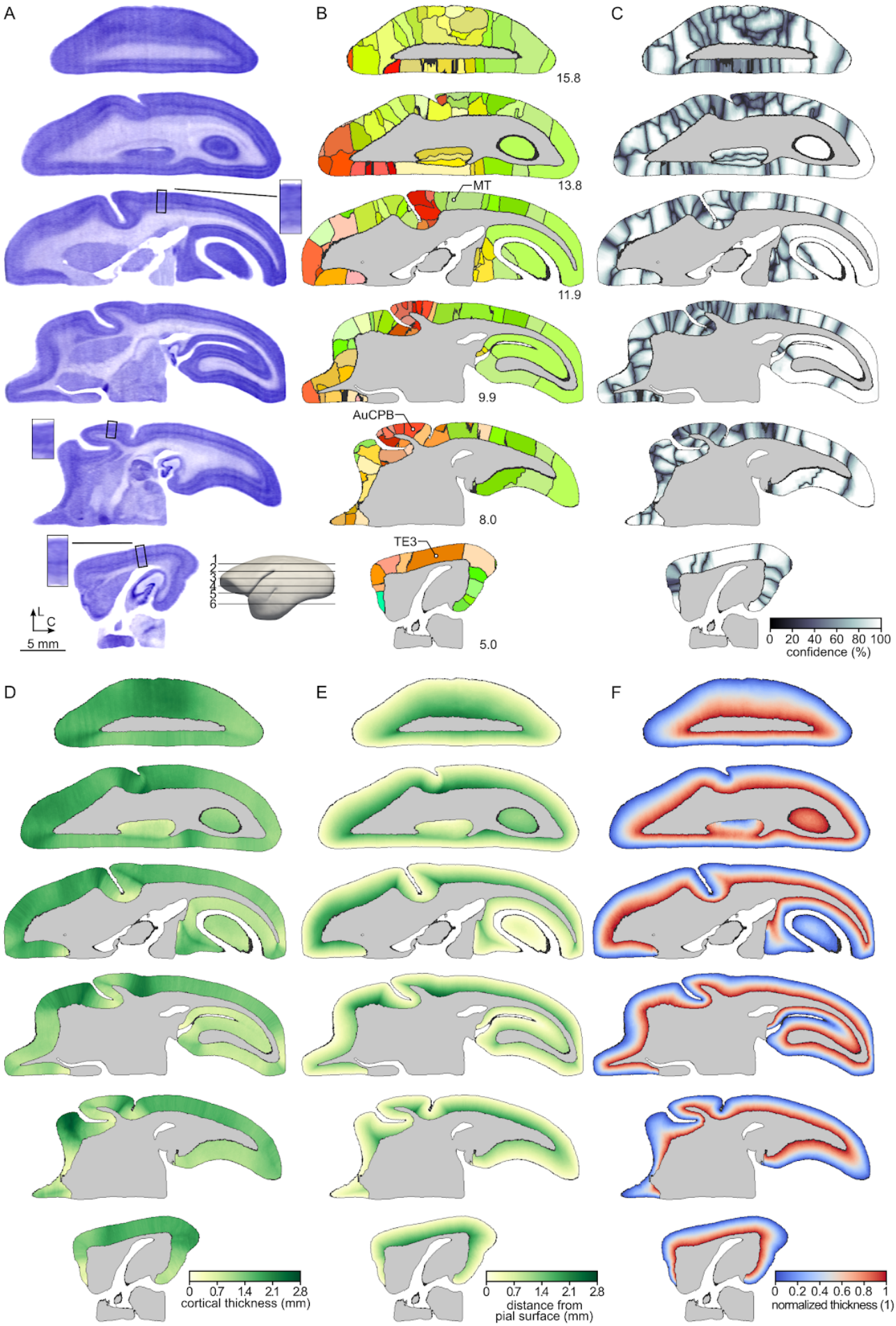


Figure S3 and S4: **Parasagittal (Fig. S3) and horizontal (Fig. S4) cross-sections at various mediolateral (Fig. S3) or dorsoventral (Fig. S4) levels illustrating the main layers of data constituting the template**. **A**: The template represented as a Nissl-stained volume. The magnified regions illustrate the laminar characteristics of selected cytoarchitectural areas labelled in panel B. Values next to each cross-section denote mediolateral (Fig. S3) or dorsoventral (Fig. S4) coordinates of the planes, which are also presented against the schematic views of the template (the gray, 3D model). **B**: Maximum-probability segmentation of the cerebral cortex into 116 areas created by selecting, for each cortical profile, the most probable label along a streamline (Fig. 3C, D). The black contours represent the borders of individual areas and are drawn for the clarity of the visualization. **C**: Segmentation confidence level map. **D**: Cortical thickness map. **E**: Depth below the pial surface. **F**: Normalized thickness map in which zero corresponds to the pial surface while one to the border between gray and white matter. All datasets are available for download from http://www.marmosetbrain.org/nencki_monash_template.


A
B
C
15.8
13.8
MT
11.9
9.9
AuCPB
8.0
TE3
5.0
L
C
5 mm
0 20 40 60 80 100
confidence (%)
D
E
F
0 0.7 1.4 2.1 2.8
cortical thickness (mm)
0 0.7 1.4 2.1 2.8
distance from
pial surface (mm)
0 0.2 0.4 0.6 0.8 1
normalized thickness (1)

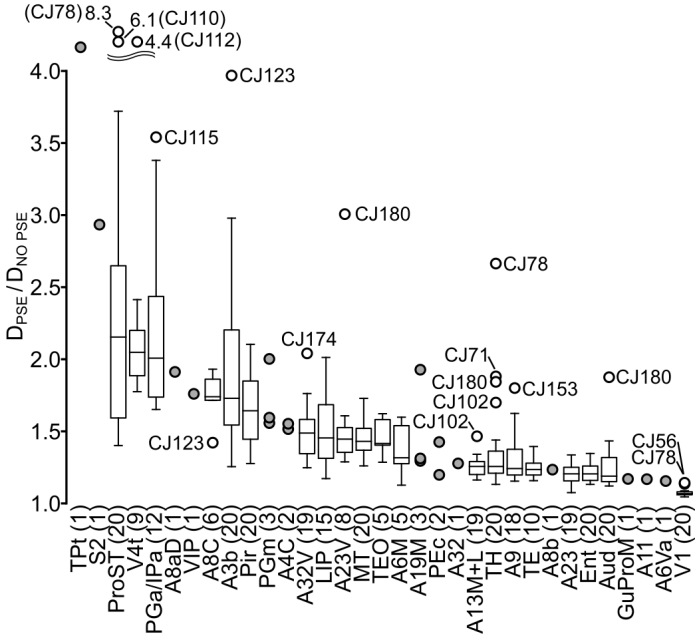


Figure S5: Improvement of the segmentation accuracy due to the incorporation of the label maps in the registration process. Comparison of the overlap between the outlines of selected cortical areas drawn manually on individual experimental cases and those of Paxinos et al. (2012) atlas after coregistration to the atlas *with* and *without* the use of label maps. D_{PSE} denotes value of Dice coefficient obtained when the label maps were used to guide the registration, $D_{NO\ PSE}$ indicates value of Dice coefficient obtained when the mapping was performed without the use of the label maps. For all examined areas, the use of label maps increased the segmentation accuracy. The improvement was particularly noticeable for smaller areas (e.g. prostriata, PGa/IPa), with complex morphology (e.g. S2, A3b) or those located deep in sulci (e.g. TPt). Areas outlined in four or more cases are presented using box plots (center line: median; box limits: upper and lower quartiles; whiskers: 1.5 × interquartile range; annotated points: outliers), while those outlined in less than four cases are plotted with gray points. Source data is available in Table S1; for a list of areas and their abbreviations see Table S2.

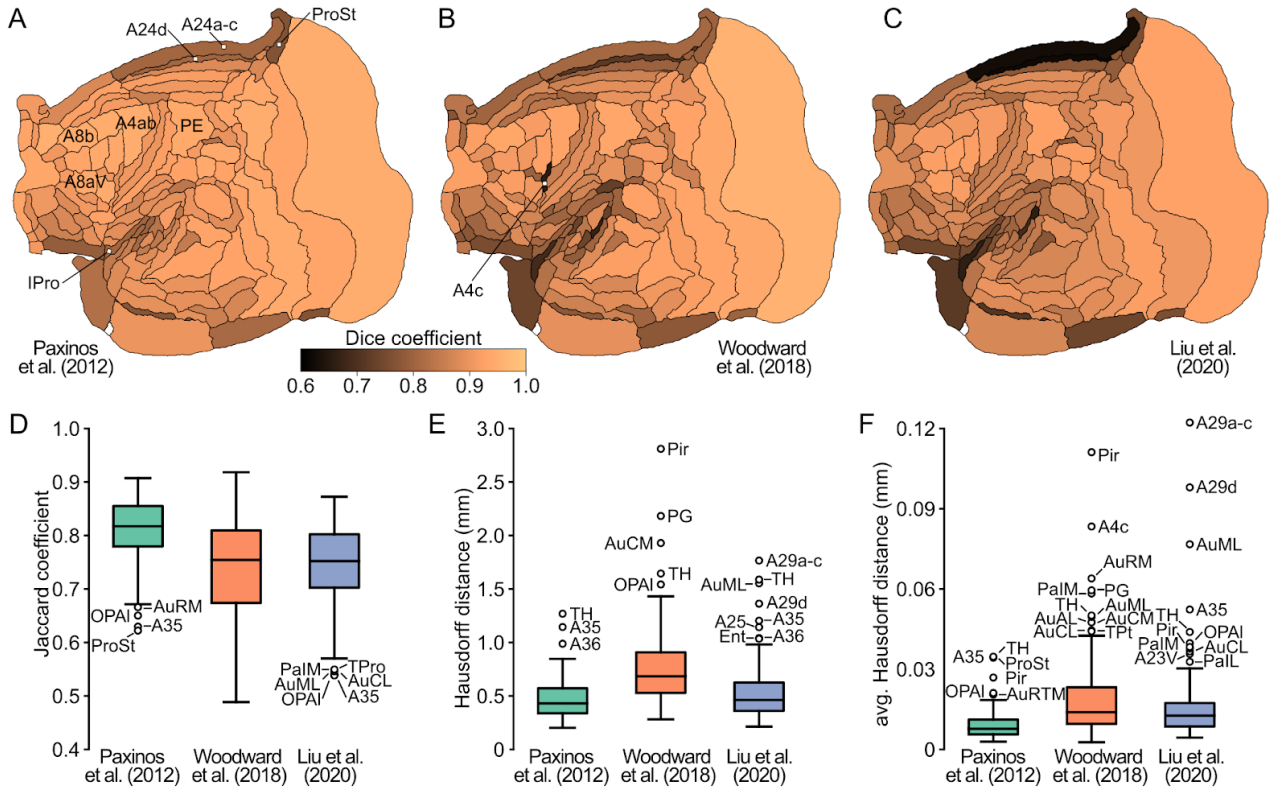


Figure S6: Evaluation of the coregistration accuracy between the Nencki-Monash (NM) template and the three other atlases of the marmoset brain. A-C: Values of the Dice coefficient measured between the segmentation of the NM template and segmentations of the other templates visualized on the flat map to illustrate the spatial pattern of the mapping accuracy. The pattern is consistent in all three cases: large areas of regular and round shape generally coregister better (e.g. A8b, A4ab, PE, A8aV) than those of irregular shape, smaller, elongated or located in the parts of the cortex that are highly curved (e.g. A29a-c, A29d, A4c, IPro). **D-F**: Evaluation of the coregistration accuracy using three additional statistics: Jaccard coefficient (D), Hausdorff distance (E), and average Hausdorff distance (F) for a more comprehensive overview of the obtained mappings. The results remain in agreement with the Dice coefficient (A-C, Fig. 8F). For a list of areas and their abbreviations see Table S2.

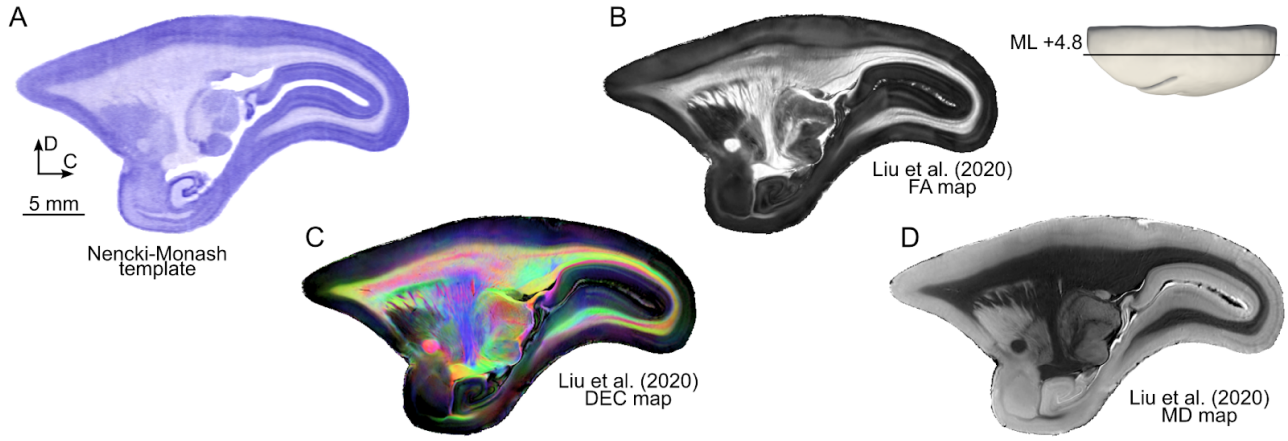


Figure S7: **Further examples of interoperability between the NM template and an *ex-vivo* MRI brain atlas.** Comparison of equivalent parasagittal cross-sections (ML +4.8 mm) of the Nencki-Monash template (**A**) with corresponding cross-sections of the diffusion MRI dataset of the MBM 2.0 atlas (Liu et. al., 2020; https://marmosetbrainmapping.org/) mapped to the NM template space **B**: Directionally encoded color (DEC) maps illustrating the fiber tracts passing in the rostrocaudal (shades of green), mediolateral (shades of red), dorsoventral (shades of blue), and diagonal (combination of the basic colors) directions. **C**: Fractional anisotropy (FA) map **D**: Mean diffusivity (MD) map. The datasets presented in this figure are available for download from http://www.marmosetbrain.org/nencki_monash_template.

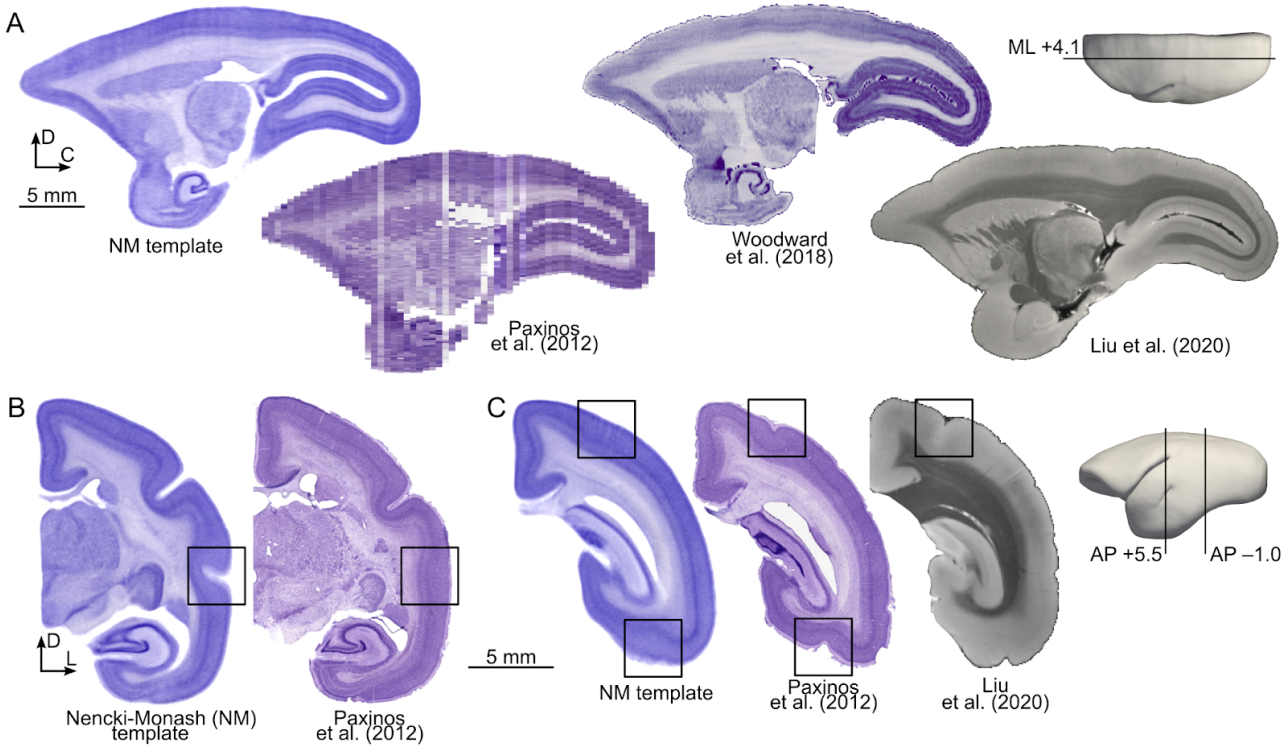


Figure S8: Equivalent stereotaxic levels in different marmoset brain templates. A: The averaging procedure employed in the present study mitigates histological artifacts that characterize templates generated from coronal (Paxinos et al., 2012) or horizontal (Woodward et al., 2018) sections. For comparison, a section obtained from an isotropic *ex vivo* MR image is illustrated (Liu et al., 2020). **B**: Comparison of equivalent coronal sections (AP +5.5 mm) demonstrate a robust superior temporal sulcus (box) in the morphological average, but not in the brain studied by Paxinos et al. (2012). **C**: At level AP -1.0 mm, the intraparietal sulcus is visible in individual brains (Paxinos et al., 2012, Liu et al., 2020), but not in the morphological average (NM template), indicating significant variability in the location of this landmark.

Table S1: Summary of label maps

The numbers indicate the improvement of registration accuracy (measured with the Dice coefficient) when a label map was applied.
For instance, a value of 1.31 means that the dice coefficient was 1.31 times higher when a label map was used in comparison when it was not.

Area Name	CJ181	CJ123	CJ122	CJ116	CJ153	CJ164	CJ174	CJ108	CJ157	CJ114	CJ115	CJ78	CJ180	CJ102	CJ112	CJ111	CJ81	CJ56	CJ110	CJ71	Number of times outlined
Area 11 of cortex	-	-	-	-	-	-	1.17	-	-	-	-	-	-	-	-	-	-	-	-	-	1
Area 13 of cortex lateral part	1.27	1.29	1.20	1.32	1.17	1.18	-	1.31	1.21	1.34	1.23	1.29	1.20	1.47	1.28	1.16	1.26	1.26	1.19	1.23	19
Area 13 of cortex medial part	1.27	1.29	1.20	1.32	1.17	1.18	-	1.31	1.21	1.34	1.23	1.29	1.20	1.47	1.28	1.16	1.26	1.26	1.19	1.23	19
Area 19 of cortex medial part	-	-	1.31	-	-	-	-	-	-	-	-	-	1.93	1.29	-	-	-	-	-	-	3
Area 23 of cortex ventral part	-	1.29	-	1.43	1.46	-	-	-	-	1.61	1.32	-	3.01	1.50	-	-	-	-	-	1.36	8
Area 23a of cortex	-	1.17	1.18	1.21	1.33	1.22	1.15	1.12	1.26	1.07	1.13	1.21	1.24	1.27	1.20	1.14	1.16	1.34	1.21	1.27	19
Area 23b of cortex	-	1.17	1.18	1.21	1.33	1.22	1.15	1.12	1.26	1.07	1.13	1.21	1.24	1.27	1.20	1.14	1.16	1.34	1.21	1.27	19
Area 23c of cortex	-	1.17	1.18	1.21	1.33	1.22	1.15	1.12	1.26	1.07	1.13	1.21	1.24	1.27	1.20	1.14	1.16	1.34	1.21	1.27	19
Area 32 of cortex	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.28	1
Area 32 of cortex ventral part	1.29	1.59	1.41	1.49	1.25	1.37	2.04	1.58	1.55	1.43	1.70	1.76	1.31	1.31	1.52	1.52	1.32	1.59	1.39	-	19
Area 3b of cortex (somatosensory)	1.59	3.97	1.64	1.93	2.98	1.61	1.46	1.93	1.53	1.33	1.25	1.82	2.40	1.55	1.55	1.48	1.99	2.21	2.20	2.37	20
Area 4 of cortex part c (primary motor)	-	-	-	-	-	-	-	-	-	-	1.52	-	-	-	-	1.55	-	-	-	-	2
Area 6 of cortex medial (supplementary motor) part	-	-	-	-	1.13	-	-	-	-	-	-	-	1.60	1.54	-	1.28	1.32	-	-	-	5
Area 6 of cortex ventral part a	1.16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
Area 8 of cortex caudal part	-	1.42	-	1.72	1.93	-	1.71	-	-	-	-	-	-	-	-	1.76	-	1.90	-	-	6
Area 8a of cortex dorsal part	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.91	-	-	1
Area 8b of cortex	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.23	1
Area 9 of cortex	-	1.19	1.24	1.15	1.80	1.62	1.27	1.19	1.24	1.23	1.43	1.41	1.21	1.17	1.22	1.25	1.26	1.49	1.18	-	18
Auditory cortex primary area	1.17	1.24	1.15	1.31	1.14	1.14	1.15	1.39	1.21	1.25	1.35	1.17	1.88	1.15	1.17	1.17	1.12	1.43	1.27	1.42	20
Auditory cortex anterolateral area	1.17	1.24	1.15	1.31	1.14	1.14	1.15	1.39	1.21	1.25	1.35	1.17	1.88	1.15	1.17	1.17	1.12	1.43	1.27	1.42	20
Auditory cortex caudolateral area	1.17	1.24	1.15	1.31	1.14	1.14	1.15	1.39	1.21	1.25	1.35	1.17	1.88	1.15	1.17	1.17	1.12	1.43	1.27	1.42	20
Auditory cortex caudomedial area	1.17	1.24	1.15	1.31	1.14	1.14	1.15	1.39	1.21	1.25	1.35	1.17	1.88	1.15	1.17	1.17	1.12	1.43	1.27	1.42	20
Auditory cortex middle lateral area	1.17	1.24	1.15	1.31	1.14	1.14	1.15	1.39	1.21	1.25	1.35	1.17	1.88	1.15	1.17	1.17	1.12	1.43	1.27	1.42	20
Auditory cortex rostral area	1.17	1.24	1.15	1.31	1.14	1.14	1.15	1.39	1.21	1.25	1.35	1.17	1.88	1.15	1.17	1.17	1.12	1.43	1.27	1.42	20
Auditory cortex rostromedial area	1.17	1.24	1.15	1.31	1.14	1.14	1.15	1.39	1.21	1.25	1.35	1.17	1.88	1.15	1.17	1.17	1.12	1.43	1.27	1.42	20
Auditory cortex rostrotemporal	1.17	1.24	1.15	1.31	1.14	1.14	1.15	1.39	1.21	1.25	1.35	1.17	1.88	1.15	1.17	1.17	1.12	1.43	1.27	1.42	20
Auditory cortex rostrotemporal lateral area	1.17	1.24	1.15	1.31	1.14	1.14	1.15	1.39	1.21	1.25	1.35	1.17	1.88	1.15	1.17	1.17	1.12	1.43	1.27	1.42	20
Auditory cortex rostrotemporal medial area	1.17	1.24	1.15	1.31	1.14	1.14	1.15	1.39	1.21	1.25	1.35	1.17	1.88	1.15	1.17	1.17	1.12	1.43	1.27	1.42	20
Entorhinal cortex	1.28	1.13	1.14	1.16	1.22	1.17	1.20	1.15	1.29	1.16	1.20	1.21	1.25	1.21	1.26	1.16	1.28	1.27	1.18	1.35	20
Gustatory cortex	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.17	-	-	-	-	1
Lateral intraparietal area of cortex	-	1.29	-	1.45	1.41	1.50	1.44	1.71	1.52	1.65	1.17	-	1.78	1.29	1.90	-	-	2.01	1.27	1.34	15
Parietal area PE caudal part	-	-	-	-	-	-	-	-	-	1.20	-	-	-	-	-	-	1.43	-	-	-	2
Parietal area PG medial part (cortex)	-	1.59	-	-	1.56	-	-	-	-	-	-	2.00	-	-	-	-	-	-	-	-	3
Parietal areas PGa and IPa	-	2.57	2.39	-	1.80	1.97	1.68	3.38	1.65	1.71	3.54	-	-	-	1.75	-	-	2.05	2.13	-	12
Piriform cortex	1.55	1.49	1.41	1.37	1.89	2.10	1.90	1.28	1.98	1.43	1.83	1.72	1.68	1.52	2.04	1.60	1.45	1.83	1.36	1.77	20
Proisocortical motor region (precentral opercular cortex)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.17	-	-	-	-	1
Prostriate area	2.48	2.27	2.04	2.67	2.51	1.40	1.51	1.63	1.44	1.56	1.58	8.29	3.72	1.60	2.28	1.96	1.62	2.64	6.05	3.13	20
Secondary somatosensory cortex external part	-	-	-	2.93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
Secondary somatosensory cortex internal part	-	-	-	2.93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
Secondary somatosensory cortex parietal rostral area	-	-	-	2.93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
Secondary somatosensory cortex parietal ventral area	-	-	-	2.93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
Temporal area TE1 (inferior temporal cortex)	-	1.21	-	1.28	-	-	-	1.25	1.28	1.34	1.39	-	1.19	1.16	-	-	-	1.22	-	1.19	10
Temporal area TE2 (inferior temporal cortex)	-	1.21	-	1.28	-	-	-	1.25	1.28	1.34	1.39	-	1.19	1.16	-	-	-	1.22	-	1.19	10
Temporal area TE3 (inferior temporal cortex)	-	1.21	-	1.28	-	-	-	1.25	1.28	1.34	1.39	-	1.19	1.16	-	-	-	1.22	-	1.19	10
Temporal area TE occipital part	-	-	-	-	-	-	1.42	1.29	1.58	-	-	-	-	-	1.62	-	-	-	1.40	-	5
Temporal area TH	1.33	1.19	1.24	1.28	1.34	1.14	1.44	1.19	1.24	1.25	1.15	2.66	1.84	1.70	1.24	1.26	1.13	1.34	1.22	1.88	20
Temporoparietal transitional area	-	-	-	-	-	-	4.16	-	-	-	-	-	-	-	-	-	-	-	-	-	1
Primary visual cortex	1.08	1.08	1.07	1.07	1.09	1.04	1.06	1.05	1.06	1.06	1.06	1.14	1.06	1.07	1.08	1.06	1.06	1.14	1.06	1.08	20
Visual area 4 transitional part (middle temporal crescent)	-	1.89	1.78	1.87	-	2.20	2.41	2.05	-	2.12	1.89	-	-	-	4.42	-	-	-	-	-	9
Visual area 5 (middle temporal area)	1.46	1.43	1.28	1.42	1.36	1.34	1.58	1.53	1.26	1.42	1.52	1.34	1.72	1.47	1.73	1.46	1.41	1.60	1.37	1.43	20
Visual area 6A (posterior parietal medial area)	-	-	-	-	-	-	-	-	-	1.20	-	-	-	-	-	-	1.43	-	-	-	2
Ventral intraparietal area of cortex	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.76	-	-	-	-	1

Areas annotated with diagonal hatching were outlined as a single, merged region.

Table S2: Abbreviations of the names of cortical areas

A1-2	areas 1 and 2 of cortex
A10	area 10 of cortex
A11	area 11 of cortex
A13L	area 13 of cortex lateral part
A13M	area 13 of cortex medial part
A13a	area 13a of cortex
A13b	area 13b of cortex
A14C	area 14 of cortex caudal part
A14R	area 14 of cortex rostral part
A19DI	area 19 of cortex dorsointermediate part
A19M	area 19 of cortex medial part
A23V	area 23 of cortex ventral part
A23a	area 23a of cortex
A23b	area 23b of cortex
A23c	area 23c of cortex
A24a	area 24a of cortex
A24b	area 24b of cortex
A24c	area 24c of cortex
A24d	area 24d of cortex
A25	area 25 of cortex
A29a-c	area 29a-c of cortex
A29d	area 29d of cortex
A30	area 30 of cortex
A31	area 31 of cortex
A32	area 32 of cortex
A32V	area 32 of cortex ventral part
A35	area 35 of cortex
A36	area 36 of cortex
A3a	area 3a of cortex (somatosensory)
A3b	area 3b of cortex (somatosensory)
A45	area 45 of cortex
A46D	area 46 of cortex dorsal part
A46V	area 46 of cortex ventral part
A47L	area 47 (old 12) of cortex lateral part
A47M	area 47 (old 12) of cortex medial part
A47O	area 47 (old 12) of cortex orbital part
A4ab	area 4 of cortex parts a and b (primary motor)
A4c	area 4 of cortex part c (primary motor)
A6DC	area 6 of cortex dorsocaudal part
A6DR	area 6 of cortex dorsorostral part
A6M	area 6 of cortex medial (supplementary motor) part
A6Va	area 6 of cortex ventral part a
A6Vb	area 6 of cortex ventral part b
A8C	area 8 of cortex caudal part
A8aD	area 8a of cortex dorsal part
A8aV	area 8a of cortex ventral par
A8b	area 8b of cortex
A9	area 9 of cortex
AI	agranular insular cortex
AIP	anterior intraparietal area of cortex
APir	amygdalopiriform transition area
AuA1	auditory cortex primary area
AuAL	auditory cortex anterolateral area
AuCL	auditory cortex caudolateral area
AuCM	auditory cortex caudomedial area
AuCPB	auditory cortex caudal parabelt area
AuML	auditory cortex middle lateral area
AuR	auditory cortex rostral area
AuRM	auditory cortex rostromedial area
AuRPB	auditory cortex rostral parabelt
AuRT	auditory cortex rostrotemporal
AuRTL	auditory cortex rostrotemporal lateral area
AuRTM	auditory cortex rostrotemporal medial area
DI	dysgranular insular cortex
Ent	entorhinal cortex
FST	fundus of superior temporal sulcus area of cortex
GI	granular insular cortex
Gu	gustatory cortex
IPro	insular proisocortex
LIP	lateral intraparietal area of cortex
MIP	medial intraparietal area of cortex
MST	medial superior temporal area of cortex
OPAl	orbital periallocortex
OPro	orbital proisocortex
OPt	occipito-parietal transitional area of cortex
PE	parietal area PE
PEC	parietal area PE caudal part
PF	parietal area PF (cortex)
PFG	parietal area PFG (cortex)
PG	parietal area PG
PGM	parietal area PG medial part (cortex)
PGa/IPa	area PGa andIPa (fundus of superior temporal ventral area)
PaIL	parainsular cortex lateral part
PaIM	parainsular cortex medial part
Pir	piriform cortex
ProM	proisocortical motor region (precentral opercular cortex)
ProSt	prostriate area
ReI	retroinsular area (cortex)
S2E	secondary somatosensory cortex external part
S2I	secondary somatosensory cortex internal part
S2PR	secondary somatosensory cortex parietal rostral area
S2PV	secondary somatosensory cortex parietal ventral area
STR	superior temporal rostral area (cortex)
TE1	temporal area TE1 (inferior temporal cortex)
TE2	temporal area TE2 (inferior temporal cortex)
TE3	temporal area TE3 (inferior temporal cortex)
TEO	temporal area TE occipital part
TF	temporal area TF
TFO	temporal area TF occipital part
TH	temporal area TH
TL	temporal area TL
TLO	temporal area TL occipital part
TPO	temporo-parieto-occipital association area (superior temporal polysensory cortex)
TPPro	temporopolar proisocortex
TPro	temporal proisocortex
TPt	temporoparietal transitional area
V1	primary visual cortex
V2	visual area 2
V3	visual area 3 (ventrolateral posterior area)
V3A	visual area 3A (dorsoanterior area)
V4	visual area 4 (ventrolatereral anterior area)
V4T	visual area 4 transitional part (middle temporal crescent)
V5 / MT	visual area 5 (middle temporal area)
V6	visual area 6 (dorsomedial area)
V6A	visual area 6A (posterior parietal medial area)
VIP	ventral intraparietal area of cortex

Table S3: Summary of the registration parameters

			Affine		SyN				CC		PSE	
	Preprocessing	Registration resolution (µm)	Metric	Iterations	Gradient step	Regularization (displacement)	Regularization (velocity)	Iterations	Weight	Window size (vox)	Weight	Coverage
Individual cases (segmentation; Fig. 1)	median, 1 vox	75	MI	$10^3 \times 10^3 \times 10^3 \times 10^3 \times 10^3$	0.25	0.0	1.0	$10^3 \times 10^3 \times 10^3 \times 10^3 \times 200$	1.0	4	1.0	100%
Morphological averaging (Fig. 2)	—	100		N/A				200×50×50			N/A	
Registration to Paxinos et al. (2012)	median, 1 vox	100	MI	$10^3 \times 10^3 \times 10^3 \times 10^3 \times 10^3$	0.25	0.0	1.0	$10^3 \times 10^3 \times 10^3 \times 10^3 \times 200$	1.0	4	1.0	100%
Registration to Woodward et al. (2018)		75										
Registration to Liu et al. (2020)		80										

MI	Mutual Information	Avants et al., 2011
CC	Cross Correlation	Avants et al., 2008
PSE	Point set expectation	Avants et al., 2011

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