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Technical Note

Implementation of a new parcellation of the orbitofrontal cortex in the automated anatomical labeling atlas

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ABSTRACT

An alternative parcellation of the orbitofrontal cortex is described for the automated anatomical labeling atlas of Tzourio-Mazoyer et al. (2002) (Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. NeuroImage 15:273–289). The new parcellation of the orbitofrontal cortex follows the description provided by Chiavaras, Petrides, and colleagues (2000, 2001). The new atlas is available as a toolbox for SPM at http://www.gin.cnrs.fr/AAL2.

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The automated anatomical atlas (AAL) (Tzourio-Mazoyer et al., 2002) is widely used in neuroimaging research, including resting state functional magnetic resonance imaging (fMRI). The AAL is available as a toolbox (http://www.gin.cnrs.fr/AAL) for SPM (Statistical Parametric Mapping http://www.fil.ion.ucl.ac.uk/spm), with MRIcron (http://www.mccauslandcenter.sc.edu/mricro/mricron), and with the Data Processing Assistant for Resting-State fMRI (DPARSF) (Chao-Gan and Yu-Feng, 2010) (http://rfmri.org/DPARSF). A new regional parcellation of the orbitofrontal cortex in the AAL is described here following the description provided by Chiavaras, Petrides, and colleagues (Chiavaras et al., 2001; Chiavaras and Petrides, 2000) of the probabilistic locations of the sulci and gyri. Both the original atlas (aal.nii.gz) and the revised atlas AAL2 (aal2.nii.gz) are available at: http://www.gin.cnrs.fr/AAL2.

In the original AAL version, the inferior surface of the frontal lobe corresponding to the orbitofrontal cortex areas was parcellated according to the terminology for sulci proposed by Déjerine (1895) and further used by Talairach in his stereotactic atlas (Talairach and Tournoux, 1988). Chiavaras and Petrides (2000) proposed another parcellation of the orbital surface allowing comparison of the anatomy of the frontal lobe of humans with that of macaque monkeys, that includes a characterization of different types of sulcal patterns. Probabilistic sulcal maps for the human orbitofrontal cortex were then produced (Chiavaras et al., 2001). In order to implement this parcellation in the AAL, we first identified the Collins' brain pattern that corresponds to a type III according to Chiavaras and Petrides (2000). We then traced the orbital sulci corresponding to a type III in both hemispheres according to this nomenclature, as shown in Fig. 1a.

Then, using the constant sulci as limits, we delineated 4 ROIs in the orbitofrontal cortex corresponding to the left and right medial orbital gyri (MOG), anterior orbital gyri (AOG), posterior orbital gyri (POG), and lateral orbital gyri (LOG) (Fig. 1b). According to the probabilistic mapping of the orbital sulci that demonstrate that these sulci are present in the axial slices inferior to $z = -10$, we delineated the orbital gyri's ROIs on seven 2-mm thick axial slices starting at $z = -10$. In each hemisphere, the MOG is limited internally by the olfactory sulcus (os) and laterally by the medial orbital sulcus (mos); the AOG is limited internally by the os and laterally by the lateral orbital sulcus (los) and posteriorly by the posterior segment of the los and by the transverse orbital sulcus (tos); the POG anterior limit corresponds to the posterior limit of AOG and its posterior limit to the anterior limit of the olfactory cortex region (OC); the LOG is internally limited by the los (Fig. 1). Note that the deep intermediate orbital sulcus, clearly visible in each hemisphere of the Collins brain was identified but not used as a limit because it is specific to the type III pattern, while the parcellation used the constant sulci as described by Chiavaras and colleagues (Chiavaras et al., 2001; Chiavaras and Petrides, 2000). The differences of the anatomical approaches used for the parcellation of the orbitofrontal cortex in AAL and AAL2 are summarized in Table 1. In this new parcellation the orbital parts of the superior, and middle inferior frontal gyri labeled F1O and F2O in the native AAL parcellation that are located between $z = 0$ and $z = -10$ mm are now included in the F1 and F2 ROIs that are thereby larger than in the first parcellation. To avoid any confusion their names were thus changed to F1_2 and F2_2. Concerning the inferior frontal gyrus, the pars orbitalis ROI (F3O) ends at $z = -6$ in the present version, corresponding to the z level of the horizontal branch of the Sylvian fissure. The F3O name, corresponding in the present version to

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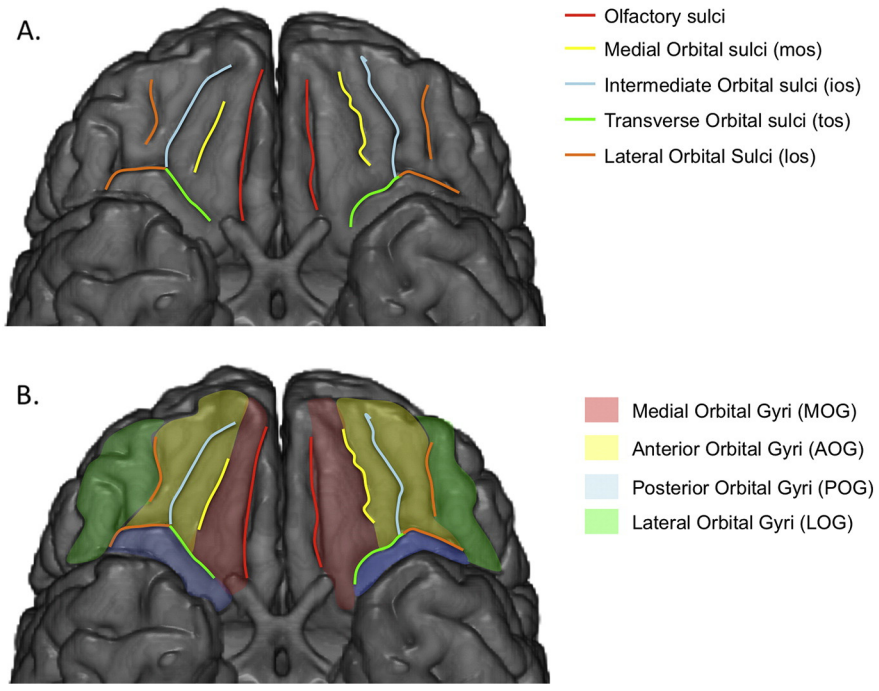

Fig. 1. Frontal lobe inferior surface, identification of sulci (A) that were used to parcellate using axial slices from −10 to −24 the new orbitofrontal regions in AAL2 corresponding to the Medial, Anterior, Posterior and Lateral orbital gyri (B).

a smaller ROI was thus modified into F3O_2. Note that this way F3O_2 is segregated from LOG. Given the role of F3O in lexical retrieval, such a split is important in the left hemisphere (see for example the meta-analysis of Vigneau et al. (2006)). Note that other frontal regions were not modified. The resulting new areas for the orbitofrontal cortex are the Medial orbital gyrus, the Posterior orbital gyrus, the Anterior orbital gyrus, and the Lateral orbital gyrus, and these are listed in italics in Table 2, as are the regions that have been modified: F1_2, F2_2 and F3O_2.

The anatomical descriptions and the corresponding labels in aal2.nii.gz are shown in Table 2 in columns 1 and 3 respectively. Column 2 shows anatomical labels related to the methodology by which the anatomical areas were defined, as described by Tzourio-Mazoyer et al. (2002) and in this paper. Column 4 shows abbreviations that may be useful when referring to each of the AAL areas in for example diagrams, as they are shorter than the anatomical descriptions provided in columns 1 and 3 of Table 2. To facilitate cross-comparison, an equivalent table for the original AAL (Tzourio-Mazoyer et al., 2002) is in Table 3.

It is noted that the Anterior and Posterior orbital gyri are sometimes grouped together as the Intermediate orbital gyrus (Mai et al., 2004). It is also noted that the division of the orbitofrontal cortex in AAL2 into the Medial orbital gyrus, in an intermediate position the Anterior and Posterior orbital gyri, and a Lateral orbital gyrus (see Fig. 1) is likely to be helpful in the analysis of the functions of the orbitofrontal cortex, in which reward-related stimuli tend to be represented medially, and non-reward and punishment-related stimuli tend to be represented laterally (Grabenhorst and Rolls, 2011; Kringelbach and Rolls, 2004; Rolls, 2014). As a guide to what these gyri include in terms of the widely used cytoarchitectonic labels, it is noted that the Medial orbital gyrus includes parts of area 13 m posteriorly and 11 m anteriorly; the Posterior orbital gyrus includes part of area 13 l; the Anterior orbital gyrus includes part of area 11 l; and that the Lateral orbital gyrus includes areas 47/12. The Lateral orbital gyrus extends laterally to abut the Inferior frontal gyrus, triangular part (area 45), which with the Inferior frontal gyrus, opercular part (area 44) and the inferior frontal gyrus orbital part included in F3O_2 contain Broca's area (in the left hemisphere) (Öngür et al., 2003; Petrides, 2014). It is also noted that the Gyrus rectus (which is medial to the medial orbital gyrus) includes medial prefrontal cortex areas 14 posteriorly and 11 m anteriorly (Öngür et al., 2003). We also note that the term ventromedial prefrontal cortex (VMPFC) is not an anatomically precisely defined area, but is usually taken to include Brodmann area 14 (in the gyrus rectus REC), medial prefrontal cortex area 10 (in the Frontal_Sup_Med and upper Frontal_Med_Orb), anterior cingulate areas 25 and 32 (in the anterior cingulate cortex ACC), and some medial parts of areas 11, 12 and 13 of the orbitofrontal cortex in the medial orbital gyrus (OFCmed) (Öngür et al., 2003; Rolls, 2014). Further information on the anatomy of the orbitofrontal cortex is available elsewhere (Mackey and Petrides, 2010; Mai et al., 2004; Öngür et al., 2003; Öngür and Price, 2000; Petrides et al., 2012; Yeterian et al., 2012).

In addition, this article includes some adjustments of the terminology used in the original paper on the AAL (Tzourio-Mazoyer et al., 2002). We provide in Table 2 a list of the nomenclature and abbreviations for the AAL2 with those that have changed from the AAL shown in red font, and in Table 3 for comparison the names used in the AAL (Tzourio-Mazoyer et al., 2002).

We provide the following notes to clarify why some of the changes are being made, and to provide some information about what is included in some of the areas, and to indicate how some terms used in the literature correspond to those used here.

The Rolandic operculum has been referred to as the subcentral gyrus (Duvernoy, 1992).

The part of the cortex just posterior to the posterior cingulate cortex is usually termed retrosplenial cortex, but is included in this atlas as part of the precuneus parcellation. We note that the retrosplenial cortex

Table 1
Inferior surface sulci defined in each hemisphere to define the ROIs limits in the 2 parcellations.

Anatomical description aal.nii.gz	Anatomical description aal2.nii.gz
Third frontal or orbital	
Fourth frontal or olfactory	Fourth frontal or olfactory
	Medial orbital
	Transverse orbital
	Lateral orbital

Table 2
List of the anatomical regions of interest defined in each hemisphere and their label in the AAL2 Atlas. The changes from the AAL to the orbital surface parcellation and the labels provided in aal2.nii.gz are shown in red. Note that F1O, and F2O are not present in AAL2, and that F3O is redefined to be smaller in AAL2 and named F3O_2 (see also text). Column 4 provides a set of possible abbreviations for the anatomical descriptions.

Anatomical description	Label	Label aal2.nii.gz	Possible abbreviation
Central region			
Precentral gyrus	PRE	Precentral	PreCG
Postcentral gyrus	POST	Postcentral	PoCG
Rolandic operculum	RO	Rolandic_Oper	ROL
Frontal lobe			
Lateral surface			
Superior frontal gyrus, dorsolateral	*F1_2*	*Frontal_Sup*	*SFG*
Middle frontal gyrus	*F2_2*	*Frontal_Mid*	*MFG*
Inferior frontal gyrus, opercular part	F3OP	Frontal_Inf_Oper	IFGoperc
Inferior frontal gyrus, triangular part	F3T	Frontal_Inf_Tri	IFGtriang
Medial surface			
Superior frontal gyrus, medial	F1M	Frontal_Sup_Med	SFGmedial
Supplementary motor area	SMA	Supp_Motor_Area	SMA
Paracentral lobule	PCL	Paracentral_Lobule	PCL
Orbital surface			
Superior frontal gyrus, medial orbital	F1MO	Frontal_Med_Orb	PFCventmed
IFG pars orbitalis,	*F3O_2*	*Frontal_Inf_Orb*	*IFGorb*
Gyrus rectus	GR	Rectus	REC
Medial orbital gyrus	*MOG*	*OFCmed*	*OFCmed*
Anterior orbital gyrus	*AOG*	*OFCant*	*OFCant*
Posterior orbital gyrus	*POG*	*OFCpost*	*OFCpost*
Lateral orbital gyrus	*LOG*	*OFClat*	*OFClat*
Olfactory cortex	OC	Olfactory	OLF
Temporal lobe			
Lateral surface			
Superior temporal gyrus	T1	Temporal_Sup	STG
Heschl's gyrus	HES	Heschl	HES
Middle temporal gyrus	T2	Temporal_Mid	MTG
Inferior temporal gyrus	T3	Temporal_Inf	ITG
Parietal lobe			
Lateral surface			
Superior parietal gyrus	P1	Parietal_Sup	SPG
Inferior parietal gyrus, excluding supramarginal and angular gyri	P2	Parietal_Inf	IPG
Angular gyrus	AG	Angular	ANG
Supramarginal gyrus	SMG	SupraMarginal	
Medial surface			
Precuneus	PQ	Precuneus	PCUN
Occipital lobe			
Lateral surface			
Superior occipital gyrus	O1	Occipital_Sup	SOG
Middle occipital gyrus	O2	Occipital_Mid	MOG
Inferior occipital gyrus	O3	Occipital_Inf	IOG
Medial and inferior surfaces			
Cuneus	Q	Cuneus	CUN
Calcarine fissure and surrounding cortex	V1	Calcarine	CAL
Lingual gyrus	LING	Lingual	LING
Fusiform gyrus	FUSI	Fusiform	FFG
Limbic lobe			
Temporal pole: superior temporal gyrus	T1P	Temporal_Pole_Sup	TPOsup
Temporal pole: middle temporal gyrus	T2P	Temporal_Pole_Mid	TPOmid
Anterior cingulate & paracingulate gyri	ACIN	Cingulate_Ant	ACC
Middle cingulate & paracingulate gyri	MCIN	Cingulate_Mid	MCC
Posterior cingulate gyrus	PCIN	Cingulate_Post	PCC
Hippocampus	HIP	Hippocampus	
Parahippocampal gyrus	PHIP	ParaHippocampal	PHG
Insula	IN	Insula	INS
Sub cortical grey nuclei			
Amygdala	AMYG	Amygdala	AMYG
Caudate nucleus	CAU	Caudate	CAU
Lenticular nucleus, Putamen	PUT	Putamen	PUT
Lenticular nucleus, Pallidum	PAL	Pallidum	PAL
Thalamus	THA	Thalamus	THA

Table 3
List of the anatomical regions of interest defined in each hemisphere and their label in the AAL Atlas (Tzourio-Mazoyer et al., 2002) for comparison with those shown in Table 2 for the AAL2 atlas. Column 4 provides a set of possible abbreviations for the anatomical descriptions.

Anatomical description	Label	Label aal.nii.gz	Possible abbreviation
Central region			
Precentral gyrus	PRE	Precentral	PreCG
Postcentral gyrus	POST	Postcentral	PoCG
Rolandic operculum	RO	Rolandic_Oper	ROL
Frontal lobe			
Lateral surface			
Superior frontal gyrus, dorsolateral	F1	Frontal_Sup	SFG
Middle frontal gyrus	F2	Frontal_Mid	MFG
Inferior frontal gyrus, opercular part	F3OP	Frontal_Inf_Oper	IFGoperc
Inferior frontal gyrus, triangular part	F3T	Frontal_Inf_Tri	IFGtriang
Medial surface			
Superior frontal gyrus, medial	F1M	Frontal_Sup_Med	SFGmedial
Supplementary motor area	SMA	Supp_Motor_Area	SMA
Paracentral lobule	PCL	Paracentral_Lobule	PCL
Orbital surface			
Superior frontal gyrus, orbital part	F1O	Frontal_Sup_Orb	SFGorb
Superior frontal gyrus, medial orbital	F1MO	Frontal_Sup_Med_Orb	SFGmedialorb
Middle frontal gyrus, orbital part	F2O	Frontal_Mid_Orb	MFGorb
Inferior frontal gyrus, orbital part	F3O	Frontal_Inf_Orb	IFGorb
Gyrus rectus	GR	Rectus	REC
Olfactory cortex	OC	Olfactory	OLF
Temporal lobe			
Lateral surface			
Superior temporal gyrus	T1	Temporal_Sup	STG
Heschl's gyrus	HES	Heschl	HES
Middle temporal gyrus	T2	Temporal_Mid	MTG
Inferior temporal gyrus	T3	Temporal_Inf	ITG
Parietal lobe			
Lateral surface			
Superior parietal gyrus	P1	Parietal_Sup	SPG
Inferior parietal gyrus, excluding supramarginal and angular gyri	P2	Parietal_Inf	IPG
Angular gyrus	AG	Angular	ANG
Supramarginal gyrus	SMG	SupraMarginal	SMG
Medial surface			
Precuneus	PQ	Precuneus	PCUN
Occipital lobe			
Lateral surface			
Superior occipital gyrus	O1	Occipital_Sup	SOG
Middle occipital gyrus	O2	Occipital_Mid	MOG
Inferior occipital gyrus	O3	Occipital_Inf	IOG
Medial and inferior surfaces			
Cuneus	Q	Cuneus	CUN
Calcarine fissure and surrounding cortex	V1	Calcarine	CAL
Lingual gyrus	LING	Lingual	LING
Fusiform gyrus	FUSI	Fusiform	FFG
Limbic lobe			
Temporal pole: superior temporal gyrus	T1P	Temporal_Pole_Sup	TPOsup
Temporal pole: middle temporal gyrus	T2P	Temporal_Pole_Mid	TPOmid
Anterior cingulate & paracingulate gyri	ACIN	Cingulum_Ant	ACC
Middle cingulate & paracingulate gyri	MCIN	Cingulum_Mid	MCC
Posterior cingulate gyrus	PCIN	Cingulum_Post	PCC
Hippocampus	HIP	Hippocampus	
Parahippocampal gyrus	PHIP	ParaHippocampal	PHG
Insula	IN	Insula	INS
Sub cortical grey nuclei			
Amygdala	AMYG	Amygdala	AMYG
Caudate nucleus	CAU	Caudate	CAU
Lenticular nucleus, Putamen	PUT	Putamen	PUT
Lenticular nucleus, Pallidum	PAL	Pallidum	PAL
Thalamus	THA	Thalamus	THA

comprises two distinct areas: Brodmann areas 29 and 30 and this cortex lies in the depth of the callosal sulcus just above the splenium of the corpus callosum and then continues around the splenium and merges with the presubiculum of the posterior hippocampal region around the isthmus (Vogt, 2009). Thus, part of the retrosplenial cortex is included in the region termed “posterior cingulate cortex” although it may continue just behind the splenium region which may be included in the precuneus.

The part of the anterior cingulate cortex under the genu of the corpus callosum is the subgenual cingulate cortex, and anterior to the genu is the pregenual cingulate cortex (Rolls, 2014; Vogt, 2009).

The parahippocampal gyrus includes the entorhinal cortex and perirhinal cortex (Huntgeburth and Petrides, 2012).

Heschl's gyrus is also known as the transverse temporal gyrus (Tzourio-Mazoyer et al., 2002).

We note that the inferior parietal lobule (IPL) is the sum of the SMG, AG and P2.

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