Brain Maps Online: Toward Open Access Atlases and a Pan-mammalian Nomenclature

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Traditional print atlases for the adult (Swanson, 2004) and developing (Alvarez-Bolado and Swanson, 1996) rat brain have recently become freely available online (http://larrywswanson.com) as open access resources under the terms of a simple Creative Commons BY-NC 4.0 International License (http://creativecommons.org/licenses). Both volumes, *Brain maps: structure of the rat brain* and *Developmental brain maps: structure of the embryonic rat brain*, respectively, are out of print, and Elsevier returned all legal rights to their content, including computer graphics files for atlas maps, to the authors in 2013.

This event highlights two interrelated topics: the emerging trend of providing essential neuroinformatics tools to the community with minimal restrictions and maximal convenience; and the requirement for database tables to have systematic, internally consistent, and complete parts nomenclatures for labeling rows and/or columns if the tables are to be used most effectively by inference engines and in connectomics network analysis.

Brain atlases are indispensible tools for displaying the spatial distribution of parts (gray matter regions, white matter tracts, ventricles, and surface features) and the localization of neuroscience data related to those parts—for the same reasons that geographic atlases are indispensible for displaying the spatial distribution of surface features on the earth. Both types of atlas are by definition sets of maps, which in turn are interpretations and abstractions of physical reality that are commonly revised over time (Robinson and Petchenik, 1976). One important difference, however, is that geographic maps are much more standardized. For example, the United States Board of Geographic Names (http://geonames.usgs.gov) was established in 1890 to maintain uniform geographic name usage by the Federal Government through a complex, evolving set of rules, similar in principle to the book of rules that has evolved to establish standard names for animal species (International Commission on Zoological Nomenclature, 1999), an ongoing process dating back to Linnaeus (1758).

Brain map parceling and nomenclature are not standardized at all and as a result are chaotic and exceptionally confusing—both within and between species (Bota et al., 2003; Bota and Swanson, 2008). This situation may be improving. The adult mouse brain atlas created by Dong and the Allen Institute for Brain Science (Dong, 2007) was pioneering in that it was the first traditional, scholarly set of schematic drawings (maps) of histological sections to be published and sold in book form—and to be distributed freely on the web, which actually preceded hardcopy release by three years (Allen, 2004). The *Allen mouse brain atlas* is used as an online template for global gene expression (Lein, 2007) and connectomics data (Bota et al., 2012; Oh et al., 2014; Zingg et al., 2014) and has thus gained wide acceptance in the community.

The *Allen mouse brain atlas* used *Brain maps: structure of the rat brain* (Swanson, 2004) as a guide, and thus both atlases use very similar parcellation and neuroanatomical terminology; both books are now online, open access resources. This makes the comparison of spatial data in the two relatively closely related species much easier than before, especially because an earlier detailed mouse brain atlas published by Elsevier (Hof et al., 2000), and including computer graphics atlas files, also followed the nomenclature and parcellation scheme of Swanson (1992). From a practical standpoint, then, what the rat and mouse brains share in common and how they differ are now much easier to determine.

The first edition of *Brain maps: structure of the rat brain* (Swanson, 1992) had three novel features. First, atlas drawings or maps of histological sections were created with Adobe Illustrator, constituting the first computer graphics brain atlas. Second, comprehensive, systematic, hierarchically organized nomenclature tables of brain parts were provided. The hierarchical tables were deep in the sense that they went from the level of the nervous system at the top to the level of

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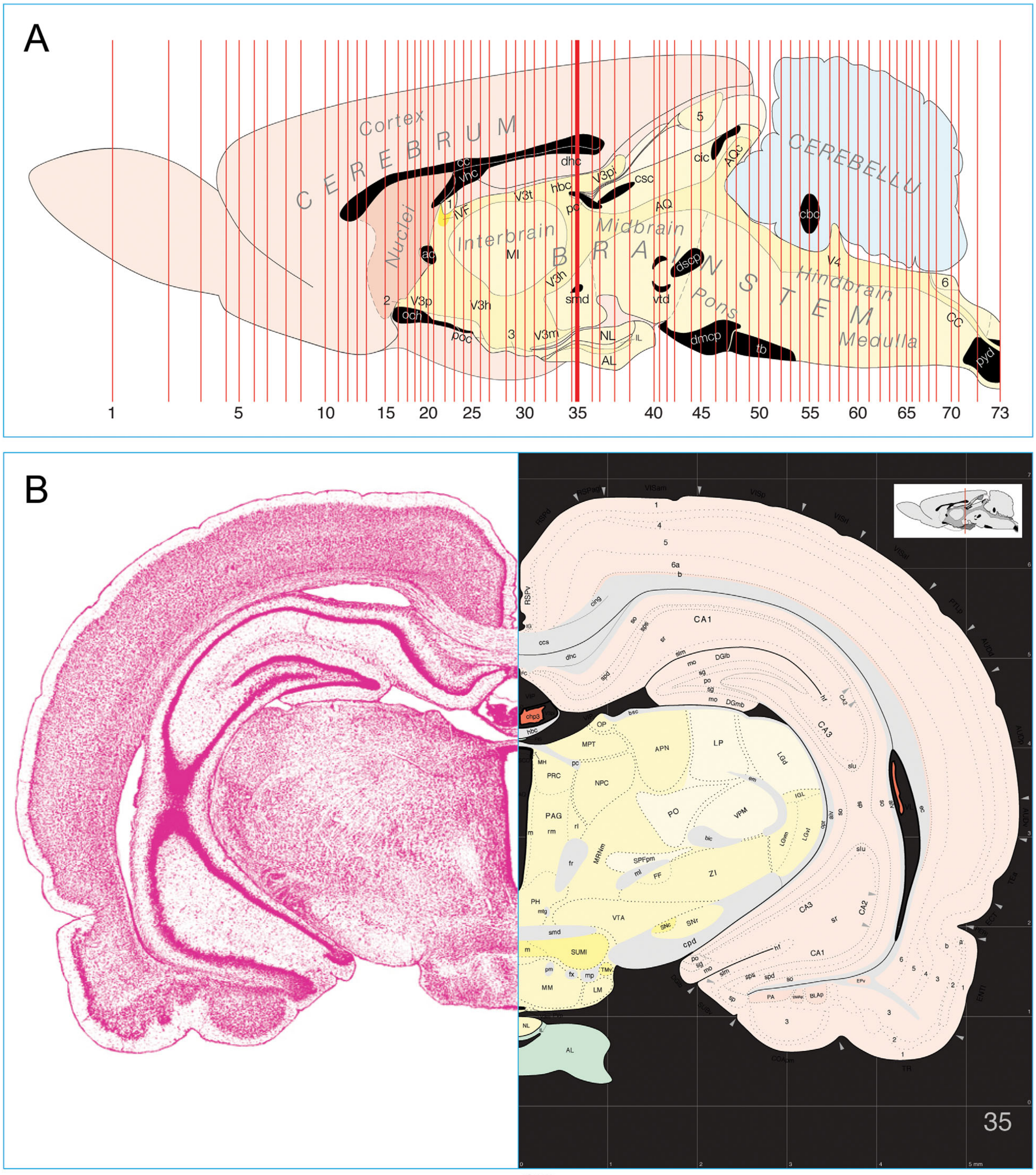

Figure 1. Illustrations from *Brain maps: structure of the rat brain*, 3rd edition (2004), now freely available online. **A**: Sagittal view of the 73 transverse Atlas Levels, with level 35 (below, **B**) highlighted. **B**: Atlas Level 35 from the *Computer graphics files 3.0* CD-ROM accompanying the book. A Nissl-stained tissue section is shown on the left, with a drawing of gray matter regions, white matter tracts, ventricles, and surface features on the right accompanied by a physical coordinates grid. Color coding on the right is for major central nervous system divisions, as shown in A and Figure 2. Size of labeling is preserved from the original files; the book was printed in tabloid format (279 × 432 mm). See the online version for easy access to abbreviations and Adobe Illustrator files for the illustrations.

gray matter regions and subregions, equivalent to species and subspecies in animal taxonomy, at the bottom. Because of these features, the nomenclature tables became fundamental to neuroinformatics database development (Dashti et al., 1997, 2001; Burns et al., 2006; Bota et al., 2003, 2014). Third, a bilateral

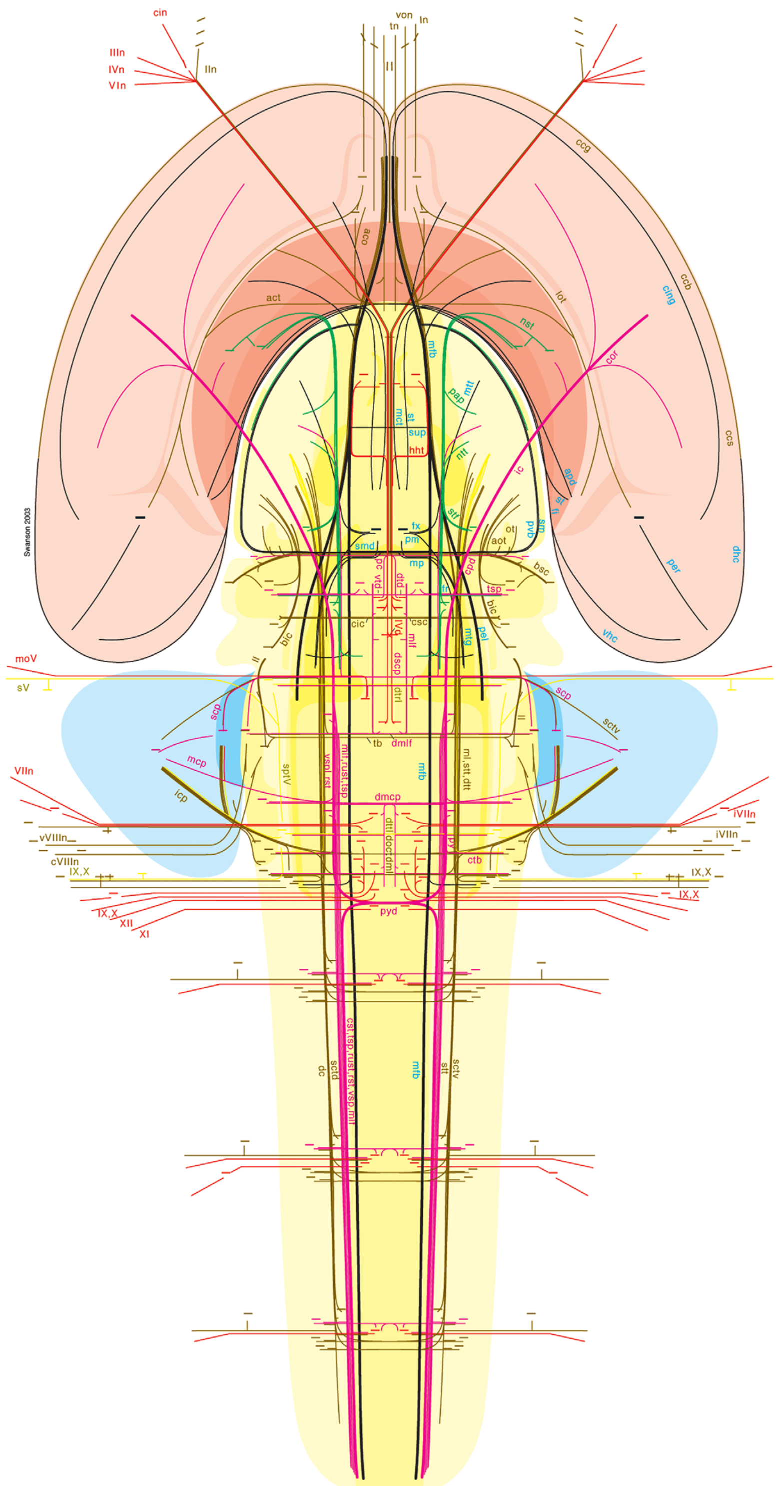

Figure 2. Frontispiece of *Brain maps: structure of the rat brain*, 3rd edition (2004) showing the major white matter tracts of the rat nervous system arranged on a flatmap of the central nervous system, with gray matter regionalization hidden for clarity. Size of labeling is preserved from the original files; the book was printed in tabloid format (279 × 432 mm). See the online version for easy access to abbreviations and an Adobe Illustrator file for the illustration.

flatmap of gray matter regionalization for the adult rat central nervous system was presented. A year later, the Adobe Illustrator files were made available on floppy discs as *Brain maps: computer graphics files* (Swanson, 1993). Two revised editions of *Brain maps* (each with book and computer graphics files on CD-ROM) then followed (Swanson, 1998, 2004). In parallel, Alvarez-Bolado and Swanson (1996) published a comprehensive atlas of rat brain development integrated with the nomenclature and parcellation used for the adult rat brain.

The third edition of *Brain maps* (Swanson, 2004) was enhanced with improved atlas graphics (Fig. 1), a flatmap with all major white matter tracts (Fig. 2) added to the earlier gray matter regionalization, and a new nomenclature table (Table A in Swanson, 2004) for major parts of the nervous system as applied to all mammals. The latter feature could be used as a starting point for developing a rigorous, systematic, and deep pan-mammalian neuroanatomical nomenclature at the level of gray matter regions, white matter tracts, ventricles, and surface features.

One important step in creating a pan-mammalian neuroanatomical nomenclature involves developing a deep common nomenclature for rodents and humans because currently the vast majority of basic neuroscience research is done in rodents at the microscopic level, whereas extensive cognitive–clinical research in humans is done at the macroscopic level with MRI technology. Four recent developments point in that direction.

First, a pan-mammalian brain nomenclature for upper, more general, levels of the hierarchy has, as mentioned, been proposed (Swanson, 2004). Second, as discussed above, a deep and compatible rat/mouse brain nomenclature has been developed and made freely available online. Third, a comprehensive set of hierarchical nomenclature tables for the human nervous system has been published recently (Swanson, 2014). These tables were designed to be compatible with pan-mammalian nomenclature, except for the cerebral cortex, where a macrolevel parceling based on traditional lobes, gyri, and sulci was used. Fourth, a provisional correspondence between rat and human cortical regionalization has recently been proposed (Bota et al., 2015), based essentially on Brodmann's work (Šimić and Hof, 2015). However, a systematic, documented, practical bridge between rodent and human neuroanatomical nomenclature and a broader pan-mammalian nomenclature remains to be formulated. In the meantime, considerable ambiguity could easily be avoided if authors would simply document clearly the source of the neuroanatomical terminology or nomenclatures (Bota and Swanson, 2010; Swanson and Bota, 2010) used in their papers.

The open access availability of the previously published, traditionally copyright-protected rat brain atlases is part of the rapidly expanding trend to provide essential neuroinformatics tools online with minimal restrictions and maximal convenience. The advantages of this digital age spinoff have been amply demonstrated in the molecular biology–genomics domain. It is only a matter of time before the neuroscience–connectomics domain benefits to the same extent—with open access neuroanatomical tools for mouse (Allen, 2004) and human (http://freesurfer.net/) brain providing useful examples.

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