Cortical Cartography

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Architecture is one part science, one part craft and two parts art. - David Rutten

A hundred years ago Korbinian Brodmann analyzed the primate brain histologically and determined that each cerebral hemisphere could be divided along features such as the presence or absence of cellular layers or distributions of Betz, stellate, granular, and other cell types. Using cytoarchitectural criteria he identified 52 areas in the monkey and 44 in the human (Brodmann 1905; 1909). Since his report more than 100,000 research papers have been published using anatomical designations (e.g., lobes, gyri, or Brodmann area, BA).

From the beginning it was assumed that different structures served disparate functions, much like a hand is made for grasping and a foot for motion and balance; different structures, different functions. Brodmann's anatomical analysis was been advanced and refined to the present-day (von Economo & Koskinas, 1925; von Bonin & Bailey, 1925; Talairach & Tournoux, 1988; Petrides & Pandya, 1994; Oishi et al., 2009). In addition to anatomical designations based on gyri and sulci, the ridges and folds of the brain, we also use a 3-dimensional coordinate system that relates all points within the brain to the midline of the anterior commissure, an arbitrary point to start our measurements, point (0,0,0) in 3-dimensional (xyz) space. As is often the case in science, an arbitrary reference point gains in stature and is re-evaluated and the anterior commissure is one of the more interesting feature of mammalian evolution and in humans particularly. It ranges in size across people, a massive 7-fold variability within our species, nothing else varies so much structurally within the human brain (Demeter et al.,1988). The three most popular coordinate systems currently in use are Talairach, MNI (Montreal Neurological Institute; cf. Collins, 1994), and ICBM (International Consortium for Brain Mapping) databases, from Paris, Montreal, and Los Angeles, respectively.

Table 1. BA names, which are locations, prominent cell types, or both.	
Frontal Lobe 4 - gigantopyramidal - “huge pyramids (cones)” 6 - agranular frontal - “lacking grains” 8 - intermediate frontal 9 - granular frontal -“composed of grains” 10 – anterior prefrontal (or frontopolar) 11 - prefrontal 12 - prefrontal 25 - subgenual* - “below the knee” 44 - opercular “little lid” 45 - triangular 46 - middle frontal 47 - orbital **Temporal Lobe** 20 - inferior temporal 21 - middle temporal 22 - superior temporal 28 - entorhinal* 34 - dorsal entorhinal * 35 - perirhinal * 36 - ectorhinal * 37 – occipitotemporal 38 - temporal pole 39 – angular gyrus 41 – anterior transverse temporal 42 – posterior transverse temporal 48- retrosubicular * 52 - parainsular * **Occipital Lobe** 17 - striate - “stripes” 18 – parastriate - “near the stripes” 19 - peristriate - “enclosing the stripes”	**Parietal Lobe** 1 – intermediate postcentral 2 – rostral postcentral 3 – caudal postcentral 5 - preparietal – “in front of the wall” 7 - superior parietal “on top of the wall” 40 – supramarginal gyrus 43 - subcentral * **Limbic Lobe** 13 – insula* 23 - ventral posterior cingulate 24 - ventral anterior cingulate 26 - ectosplenial* 29 - granular retrolimbic * 30 - agranular retrolimbic * 31 - dorsal posterior cingulate 32 - dorsal anterior cingulate 33 - pregenual * * distance and/or size of area makes accurate detection of EEG activity from scalp unlikely. <u>Other designations for Brodmann areas</u> 1-3 Primary Somatosensory Cortex 4 Primary Motor Cortex 17 Primary Visual Cortex 41 Primary Auditory Cortex 22 Wernicke’s area (varies) 44,45 - Broca's area on left hemisphere BA 14-16, 27, 49-51 are brain areas reported in nonhuman primates.

We’ve been well aware of individual differences in brain localization well before Paul Broca’s series of aphasic patients in the1860s (Morgagni, 1761; Bouillaud, 1825). One of the first aphasic patients Broca examined had a congenital defect that led to articulation problems (aphasia) in response to a right frontal lobe injury. Because of intrinsic neurophysiological variability, functional correspondence across individuals is hazardous at the level of voxels, although for general baseline conditions (eyes open rest, eyes closed rest), this is less the case.

The Brodmann montage was developed with this limitation in mind, an attempt to be as accurate as possible for use in normative EEG assessment, neuropsychology correspondence, and neurotherapy (Kaiser, 2007). The Brodmann montage is an advance on the spherical harmonic expansion model of energy distribution (Pascual-Marqui et al, 1988), a weighted-average solution, which itself was an advance over the infinitely-distant source model of Hjorth (1975; 1980). Pascual-Marqui went on to create an inverse solution known as LORETA (low-resolution EEG tomography) which relies on 2,394 voxels or sources distributed evenly across the brain – that is, an isomorphic solution -- whereas the Brodmann montage divides the cortex to "mega-voxels", 55 center points of Brodmann areas which have sufficient size and proximity to contribute to scalp voltage, a heteromorphic solution. In the Brodmann montage all 55 sources are assumed to be constantly chattering away (i.e., generating electrical dipoles), with energy equal to their area, and the surface EEG is the composition of chatter.

Is the LORETA inverse solution with thousands of voxels more accurate than the Brodmann montage of 55 mega-voxels? Yes but no. In science we are always faced with how accurate to measure a phenomenon given its nature and we must consider the goals of our measurement to decide what to do. With the Brodmann montage we wanted an ideal depiction of divisions that would map reasonably well to the functions of all the people we would record EEG from. If humans exhibited no structural or functional variability across individuals, then we can cut up the brain into an infinite number of voxels and accurately resolve functional changes in all individuals; but this is not the case. The cortex folds and unfolds differently across individuals and added to this is the amazing diversity of structure and function for the same brain areas across individuals, ranging from reverse dominance (speech motor centers in the right hemisphere), differences due to handedness, gender, age, maturation, injury, and other factors. So considering all this variability the Brodmann solution cautions on the side of fewer sources in order to increase reliability for measuring reliable sources of activity. The voxel 9, -53, 14 , which refers to x, y, z coordinates in millimeters, falls in the right posterior cingulate gyrus for most people, though not all, in Talairach space, and in the white matter above this gyrus in MNI space, and it may serve emotional perception in one person and somato-emotional processes in another. By limiting activity to Brodmann areas instead of sub-area sections of a Brodmann area (i.e., small voxels), we also have reasonable mapping to neuropsychological evaluation data. Further divisions of Brodmann areas may be reliable, but we should prefer neuroanatomically-constrained solutions over isomorphic solutions.

In science we can easily measure (sample) a phenomenon too tightly or too loosely. We want a measure that best captures a phenomenon that suits our communication and analysis needs. For instance, if I want to estimate the number of people who are baseball fans and I make my sample chronologically or spatially very tight, I may omit a vast number of people who consider themselves fans. If my definition or measurement of what constitutes a baseball fan is whether they attended a baseball game yesterday or are sitting in the stands at a game right now, this is too tight a sample by most people standards. If my definition of a fan is anyone who has attended a major league game during their life, or everyone in New England, too many people are included who would not consider themselves baseball fans. Too tight or too loose a measurement can be unreliable, even nonsensical, which is why we often measure the middle ground of a definition, something that everyone can understand and replicate on their own. This is how I chose the reasonably large Brodmann area (BA) over the millimeter-cubed voxel used by fMRI and other technologies as the BA served communication and correspondence to other fields well (neuropsychology, neurotherapy).

Training of a Brodmann area requires triangulation of activity using multiple electrodes, though one approximation is to train at the electrode nearest each area. Figure 1 shows the 10-10 electrode position system and Figure 2 shows functions associated with each BA in lateral and medial views. Figure 3 shows the closest BA to each electrode, relying on the Brede (Nielsen, 2003) and Talaraich databases (Talairach & Tourneaux, 1988), as well as the 10-10 Talairach positions reported in Koessler et al. (2009). Brodmann area training can also be performed using other source solutions (e.g., LORETA) as long as the information is provided in real time.

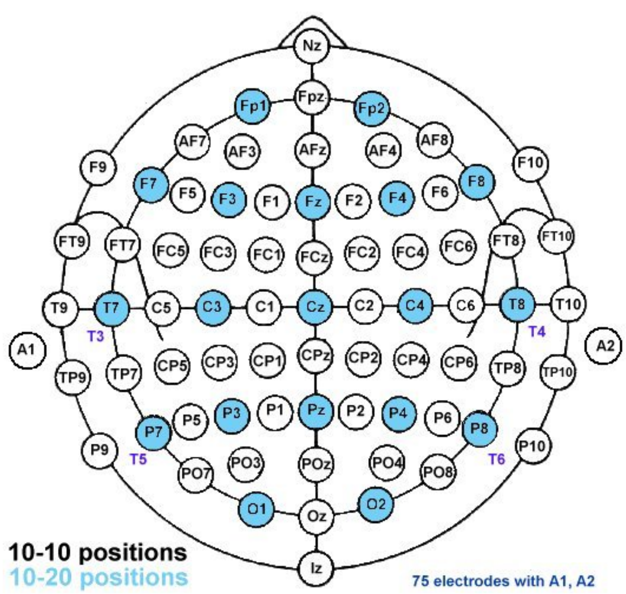

Figure 1. 10-10 electrode positions.

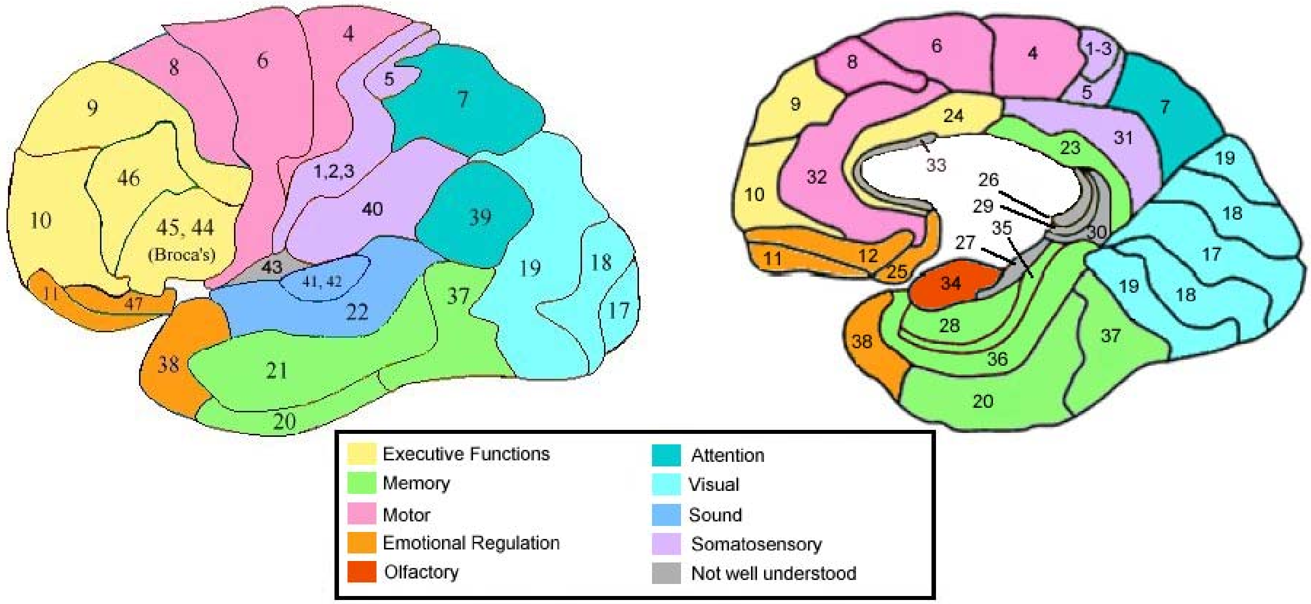

Figure 2. Brodmann areas and associated functions.

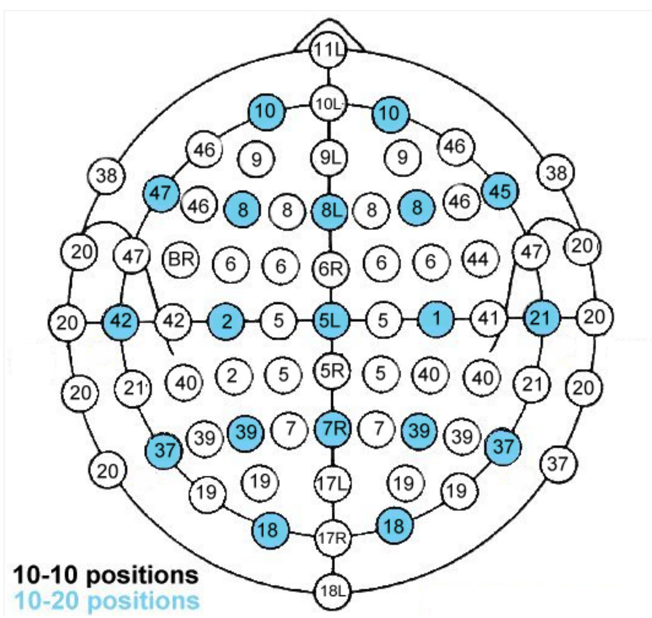

Figure 3. Brodmann area center closest to each electrode position. For instance, an effect at site C3 may be from the cortical region directly below this electrode, which is Brodmann area 2L. (BR = Broca's area)

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