Functional Specializations in Human Cerebral Cortex Analyzed Using the Visible Man Surface-Based Atlas

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Abstract: We used surface-based representations to analyze functional specializations in the human cerebral cortex. A computerized reconstruction of the cortical surface of the Visible Man digital atlas was generated and transformed to the Talairach coordinate system. This surface was also flattened and used to establish a surface-based coordinate system that respects the topology of the cortical sheet. The linkage between two-dimensional and three-dimensional representations allows the locations of published neuroimaging activation foci to be stereotaxically projected onto the Visible Man cortical flat map. An analysis of two activation studies related to the hearing and reading of music and of words illustrates how this approach permits the systematic estimation of the degree of functional segregation and of potential functional overlap for different aspects of sensory processing. *Hum. Brain Mapping 5:233–237, 1997.*

Key words: atlas; Visible Man; computerized neuroanatomy; cerebral cortex; human

INTRODUCTION

The analysis of cortical organization and function can be greatly facilitated by representing the cortical sheet as an explicit surface, thereby preserving topological relationships between neighboring points on the surface. We previously introduced [Drury and Van Essen, 1996a,b] a high-resolution, surface-based atlas of the Visible Man, a digital atlas of the human body. This atlas can be easily visualized in multiple formats (both three-dimensional and two-dimensional), linked to multiple coordinate systems (both volume-based and surface-based), and characterized by its geographical (gyral and sulcal) landmarks. It allows complex patterns of experimental data to be visualized and analyzed in relation to whichever display format is best suited to the particular issue at hand.

The Visible Man surface-based atlas is especially well-suited for analyzing results from functional neuroimaging studies. The growing flood of information about the functional organization of the human cortex from positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) requires new strategies in order to accurately compare results and synthesize them into a common framework. The current standard for reporting the location of activation foci in functional neuroimaging studies is the Talairach coordinate space [Talairach and Tournoux, 1988; Fox et al., 1985], which is based on a series of sparsely sampled sections through a postmortem brain.

Contract grant sponsor: NIH; Contract grant number: EY02091; Contract grant sponsors (joint): NIMH, NASA, NIDA; Contract grant number: Human Brain Project MH1DA52158.

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Received for publication 28 May 1997; accepted 28 May 1997

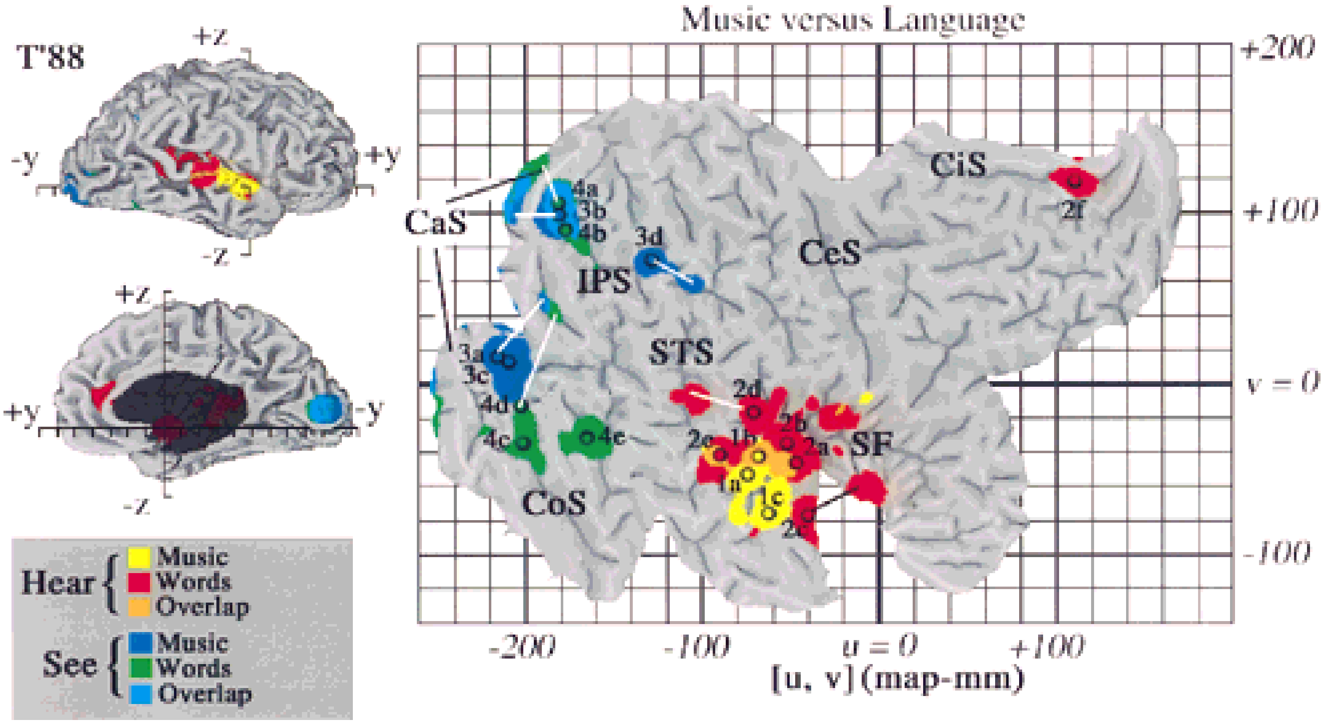

Figure 1.

Projection of activity foci from two PET studies related to hearing and reading music [Sergent et al., 1992] vs. hearing and reading words [Petersen et al., 1988]. **Left:** Lateral and medial views of the right hemisphere of the Visible Man atlas in the Talairach coordinate system. **Right:** Flat map of the Visible Man is shown, using the surface-based coordinate system. The locations of the 18 activity foci projected onto both the three-dimensional and two-dimensional surface representations are listed in Table I. Before visualization on the right hemisphere of the atlas, all left-hemisphere foci were converted to the right hemisphere by negating the x-value of their reported Talairach coordinate. The magnitude of areal distortion on the flat map varied from one region to the next; in the region circumscribing the auditory activation foci, the flat map was about 5% expanded relative to its surface area in three dimensions.

The Visible Man atlas has the advantage of a high-resolution volume reconstruction and, with the present report, an associated surface reconstruction. By associating the Visible Man atlas with the Talairach space, the visualization capabilities of cortical flat maps can be used to display and analyze activation foci reported in the Talairach coordinate space. Here we illustrate this strategy with an example that displays the activation patterns in two PET studies, one that compared reading vs. hearing music [Sergent et al., 1992], and another that compared reading vs. hearing words [Petersen et al., 1988].

METHODS

A surface reconstruction of the right hemisphere of the Visible Man cortex was derived from images of the cut-brain surface by manually tracing contours running midway through the estimated thickness of cortical gray matter. A reconstruction was generated from these contours using the Nuages software (http://www.inria.fr/prisme/personnel/geiger/nuages.html) and CARET (Computerized Anatomical Reconstruction and Editing Tools) software as previously described [Drury et al., 1996]. The reconstruction for the right hemisphere of the Visible Man contains 53,833 nodes (with an average internode spacing of 1.33 mm). Application of our multiresolution flattening method [Drury et al., 1996] resulted in a cortical flat map with a mean distortion ratio of 1.09 (on average, there is a 9% expansion of the two-dimensional map relative to the tile areas in the undistorted three-dimensional surface representation). Only 4.5% of the surface tiles are expanded by >50% (distortion ratio >1.5), and only 2.4% are compressed to an equivalent degree (distortion ratio <0.67). In general, the extent of different regions on the flat map is a good approximation to the actual surface area in three dimensions (see Fig. 1 and Van Essen and Drury [1997]).

To establish a standard coordinate system for the Visible Man atlas we used Spatial Normalization software http://ric.uthsca.edu/projects/spatialnormalization.html to transform both the surface and volume data [Lancaster et al., 1995] to the Talairach coordinate system. The transformation entailed rotations and translations to make the anterior-commissure-posterior commissure (AC-PC) line coincident with the x-axis and to place the origin at the anterior commissure. A scaling was also performed to make the cerebrum of the Visible Man atlas equal in overall dimensions to that of the Talairach atlas. This entailed expanding the Visible Man brain by 3% along the x-dimension, 1% in the z-dimension, and 0% in the y-dimension.

The locations of activation foci from functional brain-imaging studies were determined by projecting the coordinates of each focus (reported in Talairach stereotaxic space) to the nearest point on the surface of the Visible Man right hemisphere. Activation foci were visualized on the cortical flat map by displaying the center of the focus as a circle centered on the surface tile with which it is associated. Portions of the surface that lie within 10 mm of each activation center (in the three-dimensional surface) are colored according to the type of functional activation. We have shown elsewhere [Van Essen and Drury, 1997] that this captures most of the uncertainties in spatial localization that arise from the limited resolution of the PET technique and from the inaccuracies in registration when transforming data from individual brains to the stereotaxic atlas.

RESULTS

Figure 1 shows lateral and medial views of the reconstructed surface of the right hemisphere and, on the right, a flat map of the right hemisphere (at the same scale) on which cortical geography is displayed using mean curvature. Dark streaks on the map represent ‘‘inward folds,’’ where the crease runs along the fundus of a sulcus, and light streaks represent ‘‘outward folds,’’ where the crease runs along the crown of the gyrus. Several sulci are identified, including the central sulcus (CeS), superior temporal sulcus (STS), intraparietal sulcus (IPS), collateral sulcus (CoS), Sylvian fissure (SF) on the lateral side, and the cingulate (CiS) and calcarine (CaS) sulci on the medial side. Axes on the three-dimensional (3-D) reconstruction represent distances in the Talairach stereotaxic space (T′88). Axes on the flat map provide a surface-based coordinate system whose origin is at the ventral tip of the central sulcus. The axes are designated as [u,v], with u denoting the position along the horizontal and v denoting the position along the vertical axis. The grid divisions are drawn at intervals of 20 map-mm; these units differ from actual geodesic distances in the cortex anywhere that the flat map is expanded, compressed, or sheared relative to the 3-D representation.

Because the Visible Man surface was transformed to the Talairach coordinate space, the visualization capabilities of cortical flat maps can be readily utilized to analyze functional imaging data. To illustrate the approach, we selected two studies from the BrainMap data base (http://ric.uthscsa.edu/projects/brainmap) to allow comparison of visual and auditory processing of both music and words. In particular, Sergent et al. [1992] compared blood flow changes for hearing vs. reading music, and Petersen et al. [1988] compared blood flow changes for hearing vs. reading single words.

In Figure 1, each of the 18 reported activation foci for these task comparisons is identified by a labeled circle at the nearest point on the cortical surface and by appropriate coloration of the cortex lying within 10 mm of each focus. Regions activated by hearing include portions of the superior temporal sulcus (STS) and Sylvian fissure (SF), and the intervening superior temporal gyrus in the temporal lobe. The three foci associated with hearing music (yellow, foci 1a–1c) are concentrated in a relatively restricted region of the anterior STS, superior temporal gyrus, and temporal operculum of the Sylvian fissure. In contrast, the six foci associated with hearing words (red, foci 2a–2f) are distributed in a surrounding belt that includes the planum temporale (focus 2c), several additional foci in the Sylvian fissure (foci 2a, 2b, and 2d), and more posteriorly the STS (focus 2e). In addition, there is a single focus in the anterior cingulate sulcus (focus 2f). Orange shading on the map represents regions within 10 mm of both types of focus and thus *potentially* implicated in hearing of both words and music. Note that in some instances the shading associated with a given focus appears as multiple discrete patches. This can occur when the focus lies in the white matter between adjacent sulci (e.g., foci 2d, 3a, 3b, 3d, 4a, and 4d), or when a continuous focus is separated by one of the cuts introduced to reduce distortions on the cortical map (focus 2c).

Regions activated by vision include several foci in both the ventral and dorsal extrastriate cortex, with much more overlap for the dorsal than the ventral foci. Reading music activated two ventral foci (3a and 3c)

TABLE I. Activation foci as shown in Figure 1 for four classes of foci*

Focus	BrainMap focus identification	Task	*P*-value	Sereotaxic X (mm)	Y (mm)	Z (mm)	Surface-Based u (map-mm)	v (map-mm)
1a	BM17.1.1	Hear music	0.005	54	−13	6	−74	−55
1b	BM17.1.2	Hear music	0.005	−50	−25	9	−67	−43
1c	BM17.1.3	Hear music	0.005	−56	−4	2	−63	−76
2a	BM4.4.1	Hear words	0.03	−43	−24	15	−47	46
2b	BM4.4.2	Hear words	0.01	39	−31	13	−53	−36
2c	BM4.4.3	Hear words	0.03	−39	−4	−2	−41	−77
2d	BM4.4.4	Hear words	0.01	−50	−45	15	−69	18
2e	BM4.4.5	Hear words	0.01	58	−26	9	−89	−41
2f	BM4.4.6	Hear words	0.03	−11	32	19	113	116
3a	BM17.3.1	Read music	0.005	20	−95	2	−216	16
3b	BM17.3.2	Read music	0.005	3	−92	11	−181	97
3c	BM17.3.3	Read music	0.005	−23	−95	−3	−209	12
3d	BM17.3.4	Read music	0.005	−24	−66	38	−128	73
4a	BM4.1.1	Read words	0.03	−6	−89	11	−180	106
4b	BM4.1.2	Read words	0.03	11	−89	11	−177	90
4c	BM4.1.3	Read words	0.01	−22	−74	2	−200	−35
4d	BM4.1.4	Read words	0.01	24	−82	6	−203	−14
4e	BM4.1.5	Read words	0.01	32	−62	−4	−165	−32

* Foci 1a–1c (Hear music) and 3a–3d (Read music) are from Sergent et al. [1992]. Foci 2a–2e (Hear words) and 4a–4e (Read words) are from Petersen et al. [1988].

near the occipital pole, in and around the inferior occipital gyrus. In contrast, reading words activated three ventral foci situated more anteriorly, two in the collateral sulcus (foci 4c and 4d) and one in the middle temporal sulcus (focus 4e). Dorsally, there were three overlapping foci (light blue) in the transverse occipital sulcus, one activated by reading music (focus 3b) and two activated by reading words (foci 4a and 4b). An additional focus more anterior in the intraparietal sulcus (focus 3d) was activated by reading music.

Table I lists the 18 activation foci that are plotted in Figure 1. The first column indicates the focus identifier as used in Figure 1, and the second column contains a pointer to the BrainMap data base. For example, focus 3d originates from BM17.3.4, where BM17 is the unique BrainMap identifier for the study by Sergent et al. [1992], 3 is the experiment number within this study, and 4 is the activation focus number within the experiment. The *P*-values (reflecting statistical significance) and reported Talairach coordinates are listed for each focus (as reported in the BrainMap data base). In addition, the last two columns contain the surface-based coordinates for each focus after it has been projected to the Visible Man flat map. Activation foci that originated from both the left ($x < 0$) and right ($x > 0$) hemispheres are listed in Table I.

Altogether, this analysis supports the suggestion [Sergent et al., 1992] that at least some of the regions specialized for processing of music may be anatomically distinct from those specialized for processing language. Visualizing these regions on surface reconstructions and flat maps aids in appreciating the degree of physical separation vs. overlap. It also sets the stage for detailed comparisons of these activation patterns with those associated with various other aspects of specialized sensory processing (color, motion, etc.).

DISCUSSION

The approach to visualization of neuroimaging data outlined here offers several advantages over what can be attained using conventional stereotaxic atlases. Most importantly, one can see at a glance the spatial relationships among a variety of different activation foci. Color coding of foci gives an immediate intuitive sense of the degree of functional specialization vs. functional overlap even when the activation patterns are quite complex. Explicit labels and accompanying tabulations allow rapid identification of individual foci and extraction of key experimental details.

Another advantage of this approach is the visualization of the spatial uncertainties arising from the limited spatial resolution of neuroimaging techniques and from the registration errors that arise in transforming data from individual brains to the atlas. The cutoff of 10-mm radius used in Figure 1 is based on the empirically determined spread of points taken from studies that include the activation foci from individual subjects as well as the group means [Van Essen and Drury, 1997]. Geographical regions that are shaded in association with an activation focus (or multiple foci) are only potentially involved in that function (or combination of functions) in any individual brain. Higher-resolution methods, such as fMRI, are needed to resolve such questions unequivocally.

The exact pattern of activation foci obviously depends on the particular hemisphere used for the atlas, as can be demonstrated by projecting the same data to both the left and right hemispheres of the Visible Man [Van Essen and Drury, 1997]. This variability is not a reflection of an especially abnormal shape of the Visible Man brain, since both hemispheres in fact have a relatively normal pattern of convolutions in comparison to those illustrated by Ono et al. [1990]. Instead, the variability is inherent in the stereotaxic projection method, because conventional warping methods do not respect the topology of the cortical surface and therefore spatial resolution is compromised.

We intend to make the Visible Man atlas and the associated visualization and analysis software available on the World Wide Web. This will allow investigators to visualize any activity foci of interest on the two-dimensional map (as well as on the 3-D reconstruction). Currently, CARET software (for Silicon Graphics workstations) is freely available (http://v1.wustl.edu/caret.html). Future refinements may also link CARET software directly to data bases of neuroimaging foci, such as BrainMap. This will provide more efficient access to the rapidly expanding literature on functional brain imaging.

ACKNOWLEDGMENTS

This project was supported by NIH grant EY02091 and by joint funding from the NIMH, NASA, and NIDA under Human Brain Project grant MH/DA52158.

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