Improved Agreement Between Talairach and MNI Coordinate Spaces in Deep Brain Regions

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Abstract

Disagreement between the Talairach atlas and the stereotaxic space commonly used in software like SPM is a widely recognized problem. Others have proposed affine transformations to improve agreement in surface areas such as Brodmann's areas. This article proposes a similar transformation with the goal of improving agreement specifically in the deep brain region. The task is accomplished by finding an affine transformation that minimizes the mean distance between the surface coordinates of the lateral ventricles in the Talairach atlas and the MNI templates. The result is a transformation that improves deep brain agreement over both the untransformed Talairach coordinates and the surface-oriented transformation. While the transformation improves deep brain agreement, surface agreement is generally made worse. For areas in the vicinity of the lateral ventricle the transformation presented herein is valuable for applications such as region of interest modeling.

Key Words: ROI, region of interest, spatial normalization, Talairach, coordinate transformation, affine transformation

1 Introduction

Stereotaxic spaces make it possible to map scans from different people into a common coordinate system. Once the images are in the common space, a given spatial location in one scan should ideally correspond to the same location in any other scan. The commonly accepted reference space in use today is known as the Talairach coordinate system (Talairach and Tournoux, 1988). The Talariach atlas provides a common orientation and scaling procedure for brains. Landmark structures in the brain are used to define the origin and axes while scaling matches the size of the reoriented brain to that of the Talairach brain.

This technique is applicable even if the Talairach brain is replaced by any other suitable substitute. This technique, possibly in combination with nonlinear transformations, is what the software package SPM[1] does to map scans into a common stereotaxic space. Given the Talairach brain pre-

[1] http://www.fil.ion.ucl.ac.uk/spm/

dates modern digital scans and is not generally representative of the general population, a set of scans produced by the Montréal Neurological Institute (MNI) are used to map images into a space similar to, but different from, Talairach space.

These reference scans were supposed to be mapped into Talairach space which would have meant all scans aligned to them should likewise be mapped into Talairach space. Since the landmarks set forth in the Talairach guidelines were not easily identifiable on MRI scans, different landmarks close, but not identical, to the original landmarks were used in constructing the MNI templates. The shift in the landmarks resulted in a differently defined y-axis and origin. Moreover, when the templates are compared against the Talairach brain, there is a scale disparity, with the Talairach brain being clearly smaller than the MNI brain. Further discussion can be found in a paper by Hammers, et al. (2002), a poster by Brett, et al. (2001), or at `http://www.mni.mcgill.ca/`.

Ultimately, the disagreement between the Talairach and MNI spaces presents problems in situations such as region of interest (ROI) methods where precisely locating structures or functional areas is important. Even though the MNI templates have been officially adopted by the International Consortium for Brain Mapping, the fact remains that they do not constitute an atlas. In contrast, the Talairach atlas is currently considered the standard reference for locating structures and functional areas by the neurological community. The present treatment is devoted to developing an affine coordinate transformation aimed specifically at improving deep brain agreement between the two systems.

2 Methods

2.1 Transformations

An *affine transformation* was designed especially for deep brain structures. Before examining the details of the transformation, define

$$\Theta = (\theta_x, \theta_y, \theta_z, \theta_{rot1}, \theta_{rot2}) \,. \tag{1}$$

Given the existence of the y-axis, origin, and scale disagreement (Fig. 1), a five-parameter transformation was sought, where θ_x, θ_y, and θ_z are for scaling in the x, y, and z directions, respectively. The remaining two parameters θ_{rot1} and θ_{rot2} define a rotation that simultaneously attempts to correct the y-axis and origin problems. Specifically, the rotation is about the x-axis through an angle of $\arctan\left(\frac{\theta_{rot2}}{\theta_{rot1}}\right)$ radians with the origin of rotation defined as $(0, \theta_{rot1}, \theta_{rot2})$. For the purposes of scaling, the origin is approximately $(1.17, -20.68, 10.75)$, which is the mean coordinate value of the surface of the composite MNI brain. The surface is defined by thresholding the template and retaining the coordinates on the boundary of the thresholded image.

Thus, the rotation in matrix notation is

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} x \\ y - \theta_{rot1} \\ z - \theta_{rot2} \end{pmatrix} + \begin{pmatrix} 0 \\ \theta_{rot1} \\ \theta_{rot2} \end{pmatrix}, \tag{2}$$

where x', y', and z' are the rotated Talairach coordinates, x, y, and z are the original Talairach coordinates, $\phi = \arctan\left(\frac{\theta_{rot2}}{\theta_{rot1}}\right)$, and θ_{rot1} and θ_{rot2} are as defined above. The scaling in matrix notation is then

$$\begin{pmatrix} x'' \\ y'' \\ z'' \end{pmatrix} = \begin{pmatrix} \theta_x & 0 & 0 \\ 0 & \theta_y & 0 \\ 0 & 0 & \theta_z \end{pmatrix} \begin{pmatrix} x' - 1.17 \\ y' - (-20.68) \\ z' - 10.75 \end{pmatrix} + \begin{pmatrix} 1.17 \\ (-20.68) \\ 10.75 \end{pmatrix}, \tag{3}$$

where x'', y'', and z'' are the rotated and scaled coordinates, x', y', and z' are the rotated coordinates defined in equation (2), and θ_x, θ_y, and θ_z are the scale parameters described above.

Since the transformation is fine tuned for deep brain usage, the objective function defining Θ attempts to minimize the distance between the transformed Talairach and MNI lateral ventricle surfaces. Specifically, the objective function is the mean distance between the transformed Talairach and MNI lateral ventricle surface coordinates which is defined as

$$\overline{d}(\Theta) = \frac{1}{N} \sum_{i=1}^{N} \min_{LV_j^M \in LV^M} d\left(LV_i^\Theta, LV_j^M\right), \tag{4}$$

where $\overline{d}(\cdot)$ is the mean distance, N is the number of transformed Talairach coordinates, LV_j^M is a member of the set of MNI lateral ventricle coordinates, LV_i^Θ is a member of the set of transformed Talairach lateral ventricle surface coordinates, and $d(\cdot,\cdot)$ is the Euclidean distance between its two arguments. Examination of equation (4) reveals that each term in the summation is the minimum distance between a given transformed Talairach coordinate triplet and the entire static set of MNI surface coordinates.

The surface coordinates for the Talairach lateral ventricle were obtained from the digital Talairach atlas. Since no such atlas exists for the MNI brain, the MNI coordinates for the surface of the lateral ventricle had to be obtained manually. This was accomplished by hand mapping the lateral ventricles of a particular individual's MRI. The lateral ventricles of the MNI-152 T2 weighted template included with `SPM99` (Friston, 2002) in the canonical directory was hand mapped by visually comparing the template with the individual mapping and a photographic brain atlas (Roberts and Hanaway, 1970). The lateral ventricles are generally separable from the surrounding brain tissue because the intensity values are sufficiently different.

The final estimate of Θ was obtained with a standard iterative numerical minimization routine called `optimize`. This routine is part of the scripting language known as `R`. The complete package is freely available online at `http://cran.r-project.org/`.

The surface-tuned transformation developed by Brett (1999) attempts to improve agreement between the MNI and Talairach coordinates by using two separate linear transformations with the plane $z = 0$ dividing the two. With the MNI and Talairach anterior commissures coinciding and the MNI brain in the correct orientation in terms of roll (y) and yaw (z),, a rotation of 0.05 radians is applied to correct the pitch (x) discrepancy. Matching the tops of the brains after rotation requires scaling factors of 0.99, 0.97, and 0.92 in the x, y, and z directions respectively for the transformation above the plane $z = 0$. Using the same x and y scaling factors, a scale factor of 0.84 is used in the z direction below the plane $z = 0$. The explicit transformations are given in approach two of Brett (1999) the technical report.

2.2 Evaluation Methods

The closeness of fit of the proposed deep brain-tuned transformation with the MNI brain was compared with that of the untransformed brain and a surface-tuned transformation using the following four numerical measures. The first measured the percentage of lateral ventricle coordinates correctly falling within the MNI lateral ventricle; a higher proportion indicates better agreement. The second measure was the mean distance in mm between the MNI lateral ventricle coordinates and each of the three sets of coordinates being compared; a smaller number indicates better agreement. The last two measures were the 5^{th} and 95^{th} percentiles of individual distances in mm used to calculate the mean distance; a smaller numerical value indicates better agreement.

Numerical stability of the final estimate of Θ was investigated by using several different initial starting values for $\hat{\Theta}$ in the numerical minimization routine. Ultimately, an initial starting value of $(1, 1, 1, 1, 0)$ was used as the initial starting value of $\hat{\Theta}$ to obtain the final estimate of Θ reported above. This vector of initial values corresponds to no scaling as indicated by the first three *ones* in the vector and no rotation as indicated by the last *one* and the *zero* in the vector. One should note the final *one* in the vector can be replaced by any non-zero number a and still correspond to no rotation since $\arctan\left(\frac{0}{a}\right) = 0$ provided $a \neq 0$. More general affine transformations with as many as nine parameters were attempted with little to no reduction in the mean surface distance.

3 Results

Convergence using the initial starting vector in section 2.2 took 47 iterations with a final mean distance of 2.468 mm compared with a starting mean distance of 2.823 mm. The final numerical value of $\hat{\Theta}$ is approximately $(1.039, 0.939, 1.261, -38.808, 0.251)$. Recalling equation (1), the first three parameter estimates show slight scaling in the x and y directions and greater scaling in the z direction. The last two estimated parameters result in a rotation about $(0, -38.808, 0.251)$ of approximately -0.00633 radians or -0.363 degrees. When several different starting values were used to obtain an estimate of Θ, all reasonable starting values yielded estimates of Θ which agreed to within 3 significant digits of the estimate given above. Thus, the final reported estimate appears to be numerically stable. For ease of use, the simplified transformation obtained by substituting $\hat{\Theta}$ into equations (2) and (3) is:

$$\begin{pmatrix} x'' \\ y'' \\ z'' \end{pmatrix} = \begin{pmatrix} 1.039x - 0.04590 \\ 0.9394y - 0.005949z - 1.253 \\ 0.007983y + 1.261z - 2.491 \end{pmatrix} \tag{5}$$

Each of the evaluation measures demonstrates the deep brain-tuned transformation improves deep brain agreement (Table 1). Moreover, the gross scale disagreement in the z direction is improved by the deep brain-tuned transformation (Fig. 1). The original Talairach and surface-tuned coordinates show no lateral ventricle coordinates at extreme z values despite the clear presence of lateral ventricle coordinates in the MNI template. After applying the deep brain-tuned transformation, agreement in the lateral ventricles is clearly improved at these extreme z values (Fig. 2). Visual examination of deep brain structure overlays further demonstrates that the deep brain-tuned transformation delivers better agreement (Fig. 3). While these statements certainly apply in the deep brain region, the improvement in this area comes at the expense of worse surface agreement. The surface appears to be pushed out too far beyond the MNI brain surface by using the deep brain-tuned transformation, particularly in the z dimension (Fig. 1).

4 Discussion

The numerical and graphical evidence demonstrates the proposed deep brain-tuned affine transformation greatly improves agreement between the Talairach and MNI lateral ventricles. Before transformation, no untransformed Talairach lateral ventricle coordinates are present in the extreme axial slices of that structure. After applying the deep brain-tuned transformation, agreement is greatly improved with the MNI lateral ventricle for these same z values. Likewise, the transformation calibrated to the surface does not sufficiently scale in the z direction and exhibits the same behavior as the untransformed Talairach coordinates for these values. At the same time, the intermediate slices show the three coordinate systems perform similarly. That is, the deep brain-tuned transformation is better at the extreme z values without sacrificing agreement in the middle. Consequently, any ROI close to the lateral ventricles will greatly benefit from the proposed transformation.

The proportion of deep brain-transformed coordinates falling within the MNI lateral ventricle is not much better than that of the raw Talairach coordinates. This is not surprising since the untransformed Talairach lateral ventricle largely sits inside the MNI lateral ventricle. Likewise, there is not a substantial improvement in the mean distance between surfaces. The real improvement occurs for extreme values of the individual lateral ventricle surface distances. This is in agreement with the graphical evidence where the extreme lateral ventricle axial slices exhibit great improvement using the deep brain-tuned transformation while the intermediate slices show all three coordinate sets are generally the same.

As a caveat, our transformation is unreliable far from the deep brain region. Under the proposed transformation, coordinates near the surface of the brain may be outside the MNI brain. This seems to be more pronounced toward the bottom of the brain than the top. Thus, the proposed transformation should only be applied in the deep brain.

Overall, the Talairach coordinate transformation developed here is quite satisfactory in deep brain regions. Recall the affine transformation developed by Brett (1999) is radically different from the one developed here. This supports a conclusion that no affine transformation exists that will satisfactorily improve Talariach and MNI brain agreement on a global level. This makes sense in light of the fact the Talairach atlas was based on a post-mortem specimen. Any brain deformation resulting from removal and dissection is unlikely to be globally affine in nature. In addition, the Talairach specimen was from a 60-year-old woman with an unusually shaped cerebellum. The ideal solution to these problems is to construct and adopt a modern atlas based on digital scans of multiple individuals. Hammers et al. (2003) show great promise in developing a completely modern atlas based on scans from multiple subjects. Once these efforts are finished, ROI methods should greatly benefit.

Until such a solution exists, the deep brain-tuned transformation developed in this paper provides a substantial improvement for investigators interested in deep brain ROI methods. Applying the specific values given in the methods section will yield coordinates for voxels in the neighborhood of the lateral ventricle with greater accuracy than all other Talairach-based approaches.

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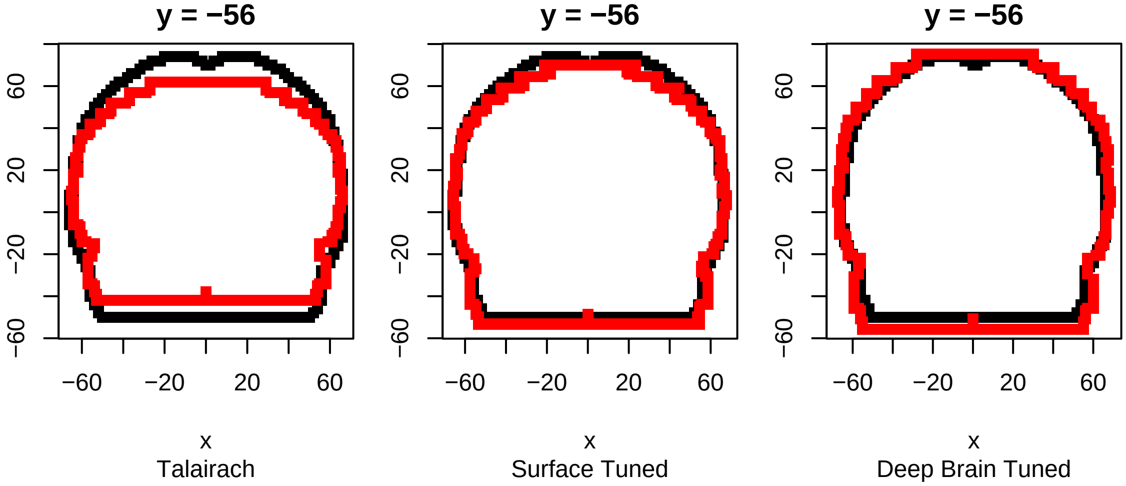

Fig. 1. Coronal surface of the MNI brain (black) compared left to right in red with the untransformed Talaiarch, deep brain-tuned transformed, and the surface-tuned transformed coronal brain surfaces. There is a discrepancy between the MNI and untransformed Talairach surfaces especially in the z direction. The deep brain-tuned transformation stretches low z values beyond the true MNI brain surface more than the surface-tuned transformation.

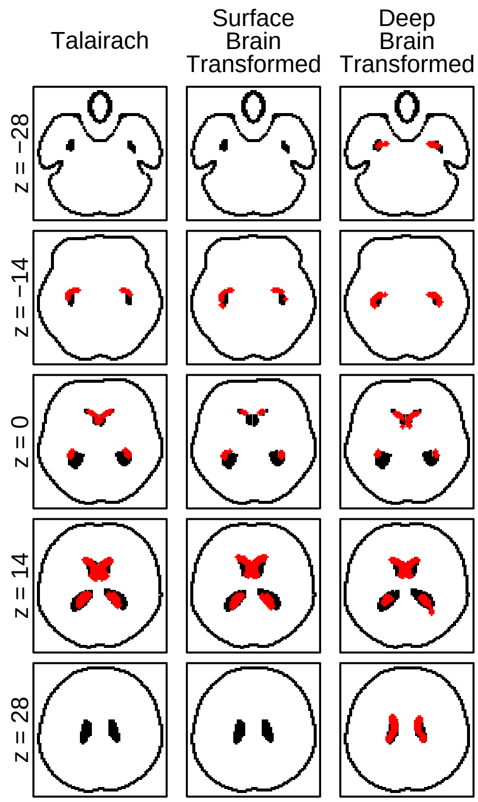

Fig. 2. The three columns from left to right correspond to the raw Talairach (green), surface brain-transformed (pink), and deep brain-transformed (blue) lateral ventricles shown in equally spaced axial slices overlaid on the MNI brain surface and lateral ventricles (black). The z value of each slice is indicated to the left of each row. Extreme lateral ventricle z values show good agreement between the deep brain-transformed and MNI lateral ventricles. In the same slices, there is a complete absence of raw Talairach and surface brain-transformed lateral ventricles.

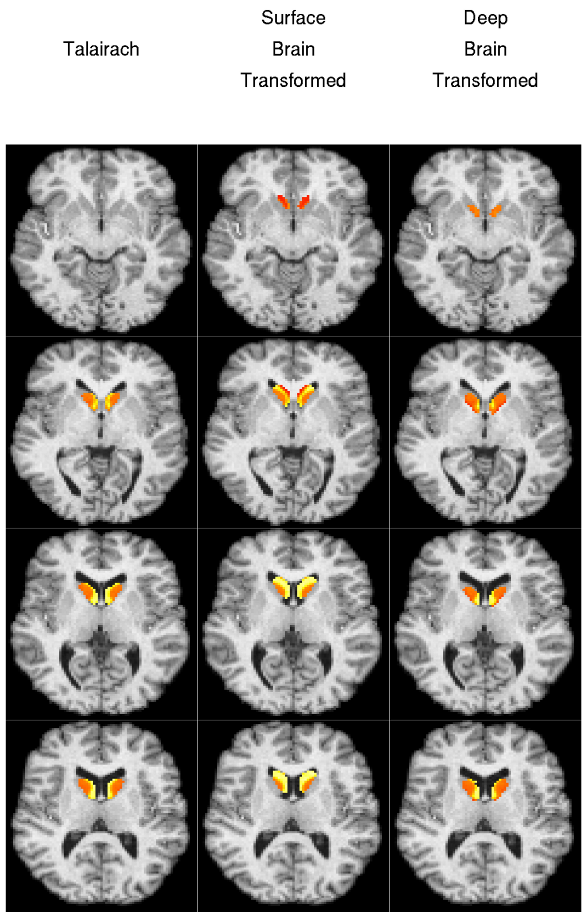

Fig. 3. Overlay of the coordinates of the caudate nucleus on axial slices of a high resolution brain MRI using untransformed Talairach, surface brain-transformed, and deep brain-transformed caudate coordinates. Orange voxels indicate legitimate gray matter within the caudate, yellow voxels indicate incursions into the lateral ventricles, and red voxels indicate incursions into white matter. The untransformed Talairach and surface brain-transformed coordinates encroach on the lateral ventricles more than the deep brain transformed coordinates. Also, the deep brain transformed coordinates cover more of the caudate for lower z values than the untransformed Talairach coordinates.

Table 1

Measures of spatial agreement between the MNI lateral ventricles and three versions of the Talairach lateral ventricles.

Measure of spatial fit	Untransformed Talairach	Surface tuned	Deep brain tuned
Voxels falling within the lateral ventricles (%)	78.6%	79.5%	81.2%
Mean distance between surface coordinates and MNI lateral ventricles (mm)	2.823	2.663 (5.7%)	2.468 (12.6%)
5^{th} percentile of distance between surface coordinates and MNI lateral ventricles (mm)	1.000	0.830 (17.0%)	0.740 (26.0%)
95^{th} percentile of distance between surface coordinates and MNI lateral ventricles (mm)	6.403	5.916 (7.6%)	5.221 (18.5%)

The values in parentheses denote the percentage improvement in the given measure over the original Talairach coordinates.