Voxel Size, Shape, and Uncertainty in Volumetric Segmentation

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Introduction

- In volumetric segmentation in MRI (particularly in the subfields of the hippocampus [HC]), there continues to be disagreement regarding the optimal voxel size for both manual and automatic segmentation.
- There is a strong preference for some manual segmentation protocols to use high resolution (small voxel size, ~0.4 mm x 0.4 mm) in-plane (coronal) voxels, where anatomy has fine detail, and thick slabs (2.0 mm) out-of-plane. Other groups prefer high resolution isotropic sequences at ~0.5 mm^3, while the standard for imaging is still 1.0 mm^3 voxels.
- **Goal:** From an instrumentation and error analysis perspective, we examine the bounds on the accuracy of segmentations of objects representative of anatomy that is typically segmented in MRI. By this we mean the limitation on estimating the true volume of an object in a voxelated space imposed by the uncertainties in the placement of voxel boundaries, and the impact voxelation has on estimating the volume of an object bounded by a 2D surface.

Methods

Investigation 1: We treat the measurement of the HC as an idealized measurement in the metrology sense, where we approximate the HC as a cuboid, with a rectangular 2:1 cross section and variable length with a fixed volume of 4600 mm^3 a typical HC volume. We calculate volume of the cuboid by measuring the location of each edge in a hypothesized discrete space determined by three representative voxel dimensions, where it is coincident with the axes of the space. The uncertainty in the measurement of the location of each edge is included via error propagation into the volume calculation of the model hippocampus as a whole, as in Equations 1 and 2:

$$V = XYZ \quad (1)$$

$$\frac{\Delta V}{V} = \sqrt{\frac{\Delta X}{X}^2 + \frac{\Delta Y}{Y}^2 + \frac{\Delta Z}{Z}^2} \quad (2)$$

Investigation 2: We simulate the effect of performing segmentation in a voxelated space on real HCs by constructing realistic HC models, simulating the effects of alignment errors during MRI acquisition, and evaluating the impact on estimated volumes (Figure 2). Five (5) high resolution hippocampal segmentations (0.3 mm isotropic) [1] were converted to surfaces with a marching cubes algorithm, and then re-meshed and smoothed using ACVD Mesh Coarsening and Resampling [2] to 10,000 vertices. The enclosed volume of these surfaces was then computed as the true volume for the HC. Each of the new reference HC surfaces was then randomly perturbed with a 3-axis translation drawn from a Gaussian distribution (μ=0 mm and σ=3 mm), and 3-axis rotation(μ=0° and σ=5°), and then projected back into a voxelated space of 0.5x0.5x0.5, 0.4x0.4x2.0 or 1.0x1.0x1.0 mm voxel shape. To handle partial volumes, any voxel with greater than 50% occupancy was included in the resulting segmentation. Volumes of each HC segmentation were then computed. The preceding process was repeated 10,000 times per HC model to produce a distribution of volumes, and the relative error was computed versus the reference enclosed surface volume.

Results Investigation 1

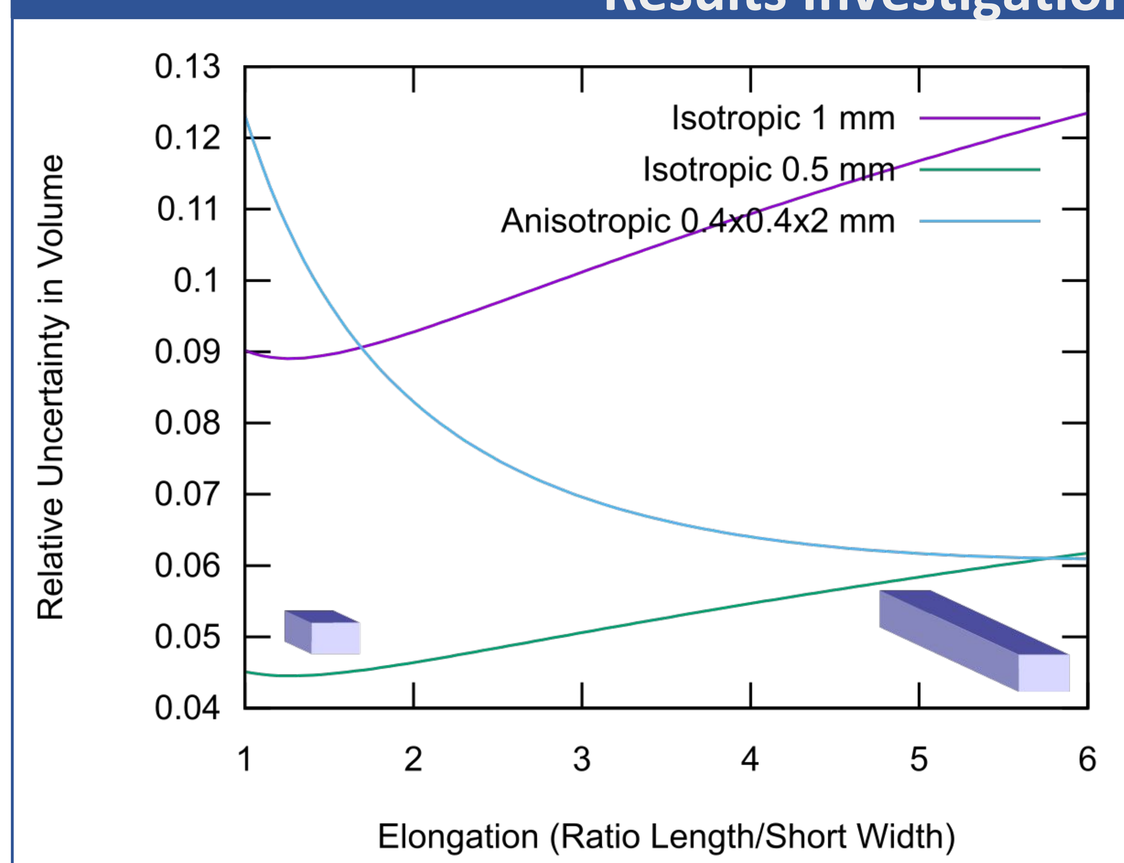

Figure 1: Theoretical uncertainty in volume of a cuboid object (model HC) in a voxelated space, as a function of the elongation of the cuboid.

With isotropic voxels, uncertainty increases with elongation, as more volume is exposed on the lengthwise surface area. The slope of uncertainty vs elongation is larger for larger voxel dimensions, but increase is linear.

In anisotropic spaces, with the elongation aligned with the thick slice direction, uncertainty decreases with elongation, in a functional for ~1/elongation.

Graphical Methods

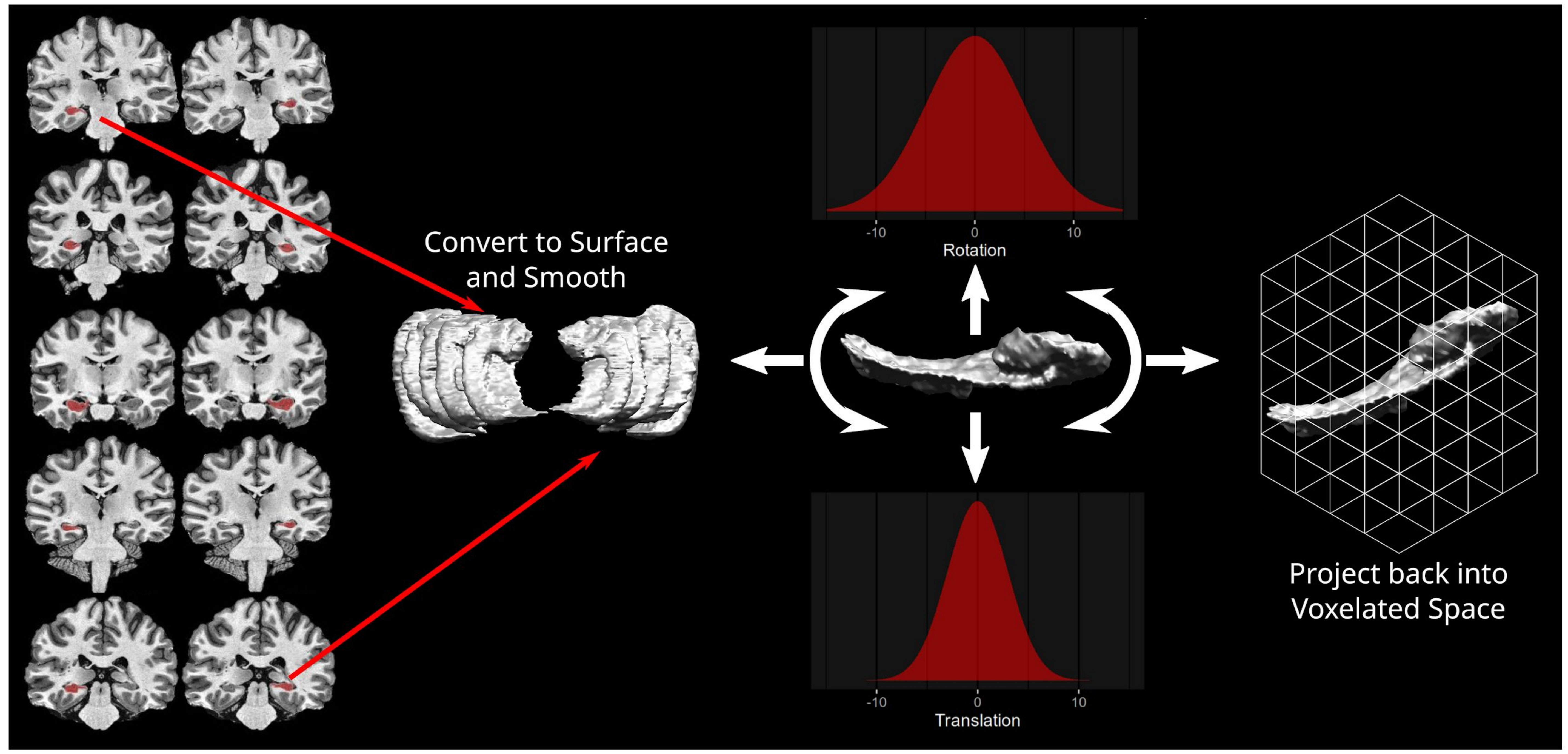

Figure 2: Graphical representation of the segmentation simulation pipeline. Individual left and right HC segmentations from 0.3 mm isotropic atlases and converted to surfaces and smoothed to remove voxelation effects. Surfaces are then perturbed with rotations and translations and projected back into a voxelated space and the volume calculated.

Results Investigation 2

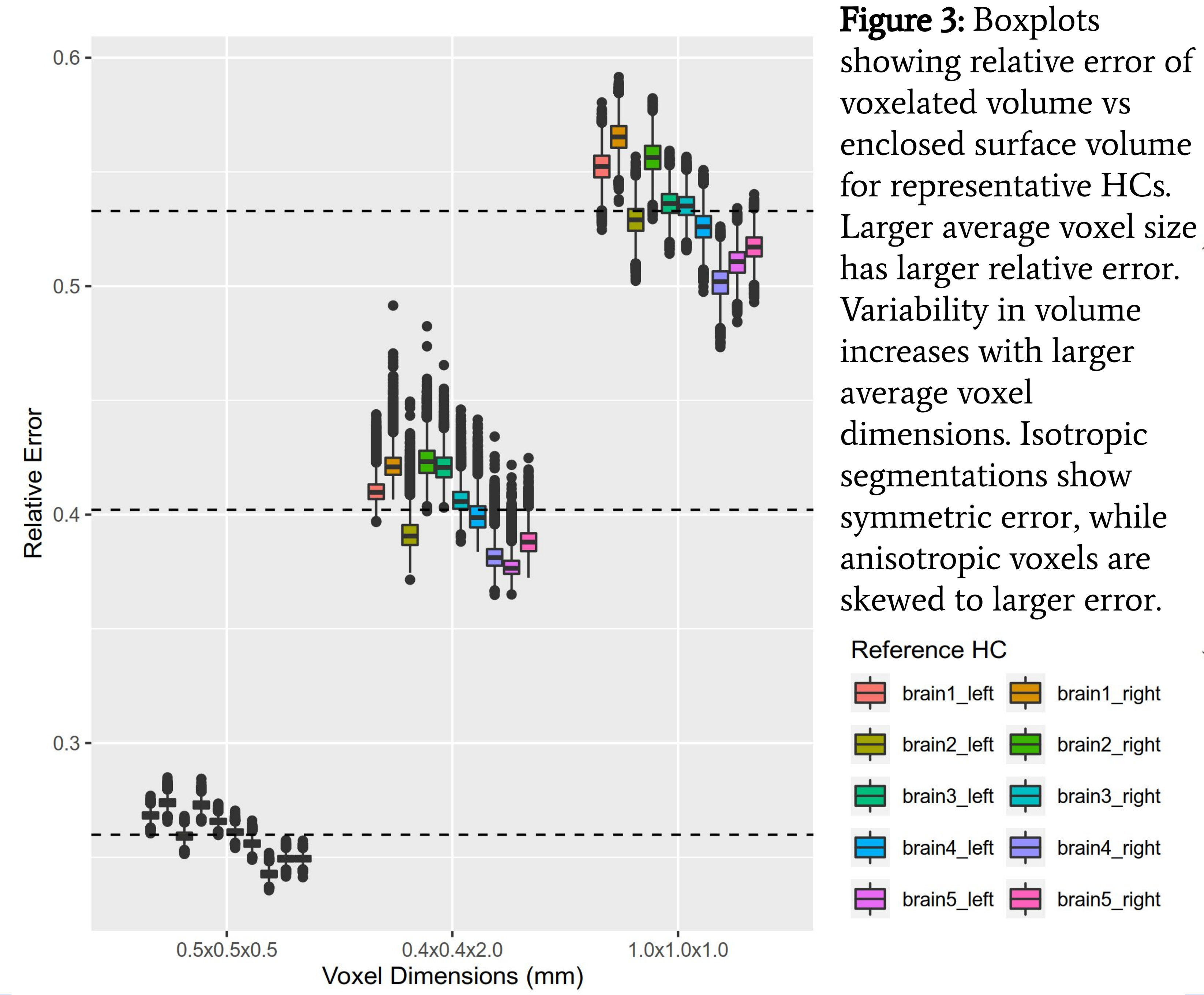

Figure 3: Boxplots showing relative error of voxelated volume vs enclosed surface volume for representative HCs. Larger average voxel size has larger relative error. Variability in volume increases with larger average voxel dimensions. Isotropic segmentations show symmetric error, while anisotropic voxels are skewed to larger error.

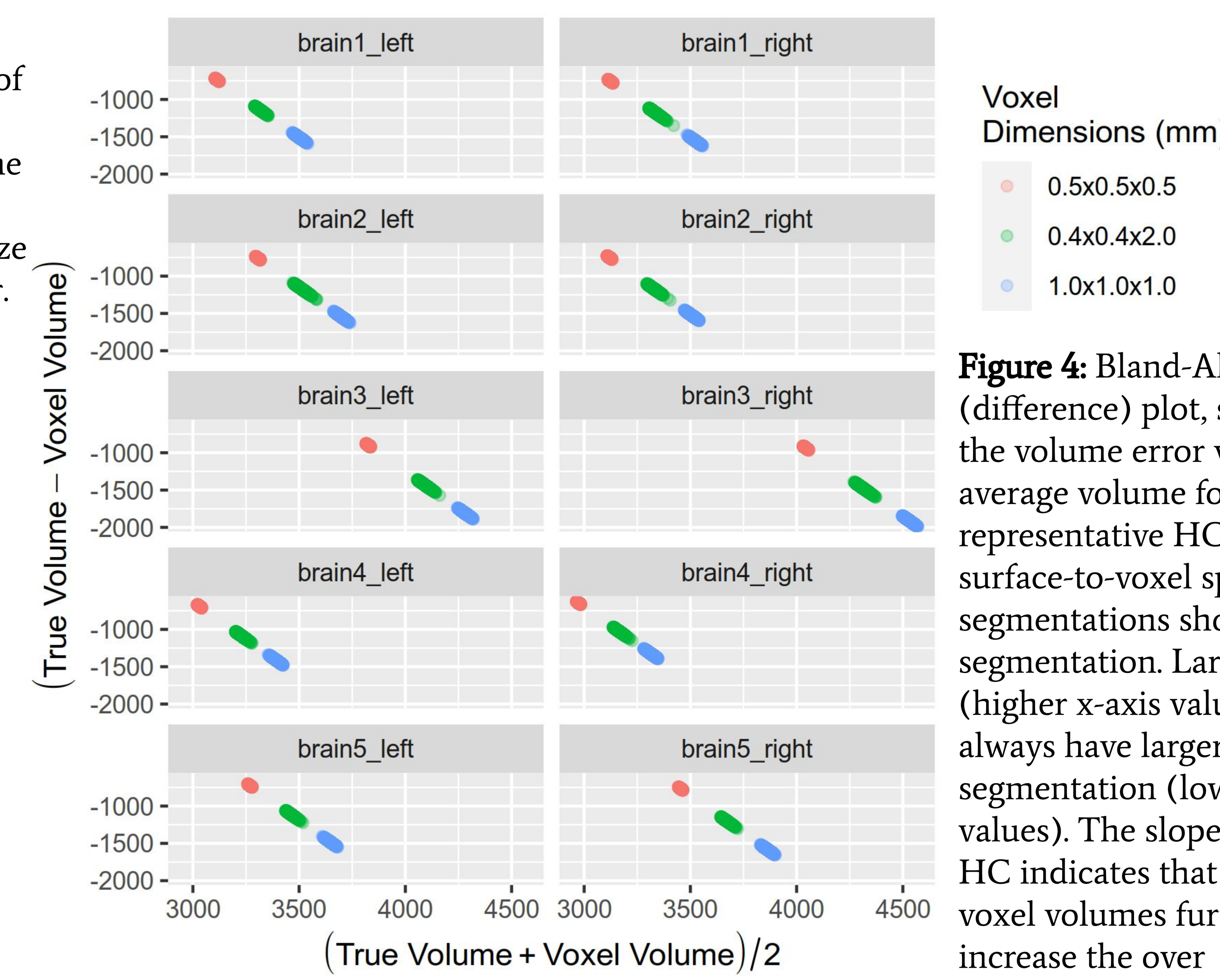

Figure 4: Bland-Altmann (difference) plot, showing the volume error vs average volume for the 10 representative HCs. All surface-to-voxel space segmentations show over segmentation. Larger HCs (higher x-axis values) always have larger over segmentation (lower y-axis values). The slope for each HC indicates that larger voxel volumes further increase the over segmentation bias.

References

[1] Winterburn JL, Pruessner JC, Chavez S, et al. A novel in vivo atlas of human hippocampal subfields using high-resolution 3 T magnetic resonance imaging. Neuroimage. 2013;74:254-65.

[2] https://www.creatis.insa-lyon.fr/~valette/public/project/acvd/

Conclusions

In this work, we examined the uncertainty and bias inherent in estimating the volume of structures in a voxelated space. There are several key conclusions from this work: 1) All voxelated segmentations oversegment structures under a 50%+1 partial volume threshold, 2) Anisotropic voxel uncertainty in volume estimation is paradoxically larger than isotropic volume estimates with larger voxel dimensions, 3) Anisotropic voxel segmentation error distributions under alignment perturbations are skewed to larger error and 4) Over segmentation bias increases with larger structures and larger average voxel dimension.