Language Pathway Homologues in Chimpanzees Reconstructed Using Diffusion Tractography

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Introduction: The white-matter tracts connecting the language centers of the brain, namely Broca's and Wernicke's areas, located in the inferior frontal gyrus and superior temporal gyrus, respectively, have been extensively studied in humans and macaques because they support language in humans [1, 2]. Recently, the homologues of Broca's and Wernicke's areas have been identified in our closest living primate relative, the chimpanzee, using histological methods [3, 4]. However, the white-matter pathways linking these two areas as well as their hemispheric asymmetry have not yet been extensively explored. In this study, we reconstructed and analyzed the white-matter pathways connecting the inferior frontal gyrus and superior temporal gyrus using probabilistic tractography in chimpanzees. This study may shed light on the origin of language in humans.

Method: ***Subjects:*** Ten chimpanzees (8 males, 2 females, age: 23±7 yrs) were included in this study. ***Image acquisition*****:** MRI images were obtained using a 3T Trio scanner (Siemens Trio, Pennsylvania, US). T1-weighted images were acquired using a 3D MPRAGE sequence with the following parameters: FOV=204×204 mm^2, matrix size: 256×256, 0.8 mm isotropic voxels. Diffusion-weighted MR images were acquired using a single-shot dual spin-echo diffusion echo-planar imaging sequence with the following parameters: FOV=130×230 mm, matrix size: 72×128, 41 slices covering the whole brain, 1.8 mm isotropic voxels, eight averages with opposite phase encoding directions to remove the susceptibility distortions [5]. ***Probabilistic tractography*****:** In order to reconstruct the white-matter pathways connecting Broca's area in the inferior frontal gyrus and Wernicke's area in the superior temporal gyrus, two ROIs were drawn as seed masks, similar to methods used by Catani et al., [6]. Guided by the DTI colormaps transformed to T1-weighted space, the seed masks were drawn over three coronal slices each in the inferior frontal gyrus and the superior temporal gyrus (Fig. 1a). Then, a waypoint mask and an exclusion mask were drawn to restrict the pathways within each hemisphere and also to the occipital/parietal lobes. Each subject's reconstructed white-matter tracts, one for each hemisphere, were normalized by the total number of remaining tracts to preserve the hemispheric asymmetry of the language pathway of each individual. Tracts were then transformed into the chimpanzee template space using an experimentally derived non-linear transformation matrix for each subject. Normalized tracts were each thresholded by 0.1% in order to remove any low probability voxels, then were binarized and averaged together to produce a probability map. For three-dimensional visualization, the probability tracts were thresholded at 60% and binarized to display only the tracts present in the majority of subjects. The asymmetry index was calculated based on the formula $AI=(L-R)/((L+R)/2)$, where L represented the tract volume or waytotal number of the pathway in the left hemisphere and vice versa.

Results & Discussion: Probabilistic tractography results (Fig. 1b-e) identified two major white-matter tracts, namely, the arcuate fasciculus (AF) and the extreme/external capsule (EmC) connecting the inferior frontal gyrus with the superior temporal gyrus, consistent with findings in humans [1], chimpanzees [7], and macaques [2]. Moreover, the preliminary qualitative results showed that, unlike in humans, the EmC seems to show stronger connectivity compared to the AF in each hemisphere in chimpanzees. The total tract volume (AF + EmC) of the language pathways showed no asymmetry in waytotal numbers (-0.473 ± 0.839, $p < 0.108$) and a trend of rightward asymmetry in tract volume (-0.480 ± 0.690, $p < 0.055$), though both measures approached conventional levels of statistical significance. For both measures, 8 of the 10 apes showed a rightward asymmetry. The larger total tract volume in the right hemisphere results mainly from the larger tract volume of the EmC in the right hemisphere, a finding consistent with a previous human study [8].

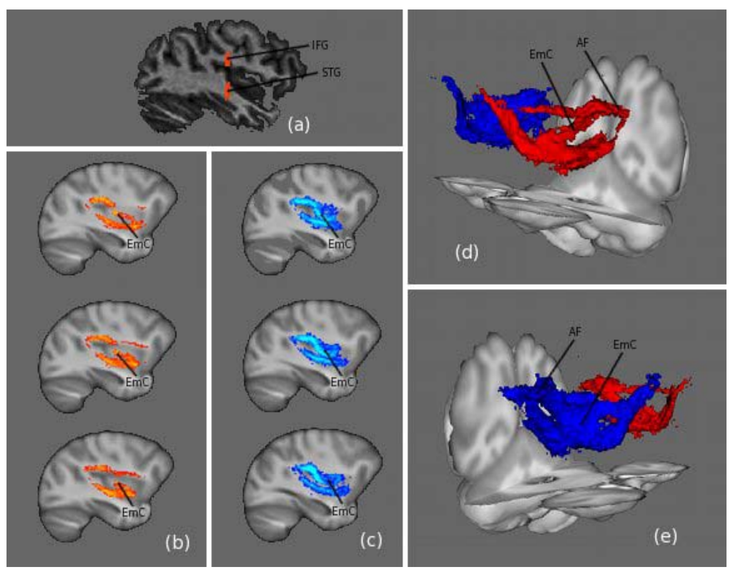

Figure 1. The probability maps for the tracts connecting the inferior frontal gyrus and the superior temporal gyrus. Example seed masks (a) drawn in the inferior frontal gyrus (IFG) and superior temporal gyrus (STG). Two-dimensional representations of the tracts displayed on a T1-weighted template brain in the left hemisphere (b) and the right hemisphere (c). Brighter pixels represent more subjects have a connection on that voxel and vice versa. Three-dimensional representations of the tracts thresholded at 60% in each hemisphere with blue color for the right hemisphere and red color for the left hemisphere angled for the

Conclusions: Consistent with a previous study [7], our study identifies two pathways, the ventrally located EmC and dorsally located AF, connecting the language homologues in chimpanzees. Further, we observed a trend of rightward asymmetry in terms of tract volume and waytotal numbers in chimpanzee's language pathway homologues and this trend is very possibly a result of rightward asymmetry in EmC, instead of AF. Further studies with a more refined methodology (i.e., separately track the two pathways), larger sample size, and diffusion data with higher resolution are necessary to confirm the current preliminary observations. If confirmed, these findings suggest that in addition to previously documented specializations in pathway size and trajectory, leftward asymmetry of the arcuate might be a distinctive human attribute.

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