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Mapping Subcortical U-fibers and Long-Range Fibers in Superficial White Matter

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INTRODUCTION.
The superficial white matter (SWM) immediately beneath the cortical mantle harbors short-range U-fibers that interconnect adjacent cortical regions, thereby supporting local information integration. Due to the key role of U-fibers in brain plasticity and aging, alterations in their density are observed in various disorders[1,2,3]. Despite its importance, the SWM has been relatively understudied compared to deep white matter, in part due to its thin, heterogeneous structure and the challenges it poses for in-vivo imaging. Recent advances in high-resolution histology and surface-based analysis, such as those enabled by ultra-high field 7T magnetic resonance imaging (MRI) and the BigBrain 3D histology dataset, have provided unprecedented opportunities to characterize SWM organization at multiple depths from the cortical surface[4]. Nevertheless, reliably separating and quantifying short-range U-fibers from long-range fibers within the SWM remains technically challenging. Building on these advancements, we adapted a framework[5] to separate and quantify short-range U-fibers and long-range fibers within the human SWM and examined how their distribution is shaped by cortical geometry.

METHOD.
This study utilized MRI data acquired at the Montreal Neurological Institute using a Siemens Terra system with both 3T and 7T scanners. The dataset comprised eleven healthy participants (4 females) with a mean age of 30.1±5.52 years. The following scans were collected: (i) 7T T1-weighted (T1w) images and (ii) 3T diffusion-weighted images. All MRI data were preprocessed using the micapipe pipeline[6]. We separated and quantified U-fibers and long-range fibers in the SWM by first solving the Laplacian equation across the white matter and shifting an existing surface along the resulting gradient using T1w-images. Using this Laplacian field, we computed streamlines extending from the white matter surface toward the subcortical regions and subsequently warped these streamlines into the diffusion MRI space. We then extracted apparent fiber density[7] values from fixels derived via multi-shell, multi-tissue fiber orientation distribution. Based on their orientation relative to the Laplacian streamlines, fibers aligned parallel were identified as radial fibers connecting the cortex to deep white matter (long-range fibers), while those perpendicular were classified as tangential to the cortex (i.e., putative U-fibers).

RESULTS.
The fiber density maps, representing the density of the corresponding fiber populations (at 2 mm underneath the gray/white matter border), are shown in Fig. 1A. To evaluate the influence of brain geometry on SWM fiber density, we examined the correlation between each fiber density map and local cortical curvature (Fig. 1B). Long-range fibers showed a mild correlation with curvature, which was not statistically significant within sulcal surfaces. In contrast, U-fibers exhibited a moderate correlation with curvature, with significant associations observed in both gyral and sulcal regions.

DISCUSSION.
Our study applied a framework for separating and quantifying U-fibers and long-range fibers within the SWM using combined 3T and 7T MRI. The findings on the influence of brain geometry on SWM fiber density are consistent with previous work[8] and suggest that cortical geometry may differentially constrain the organization of short- and long-range fibers, with this framework providing a promising tool for further refinement using histology or cytoarchitectonic data to elucidate SWM microstructure.

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