Intracortical smoothing of small-voxel fMRI data can provide increased detection power without spatial resolution losses compared to conventional large-voxel fMRI data

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Supplementary Figure captions

Supplementary Fig. 1. Illustration of the process of selecting kernel sizes that achieve a desired smoothing capacity. A simulated dataset consisting of 100 time-points of synthetic white noise (zero mean, unit variance) in 1.1 mm isotropic resolution was smoothed with kernels of different shapes and sizes, including volume-based and surface-based, and the resulting temporal standard deviation values (tSTD) were used to determine kernels of corresponding smoothing capacity. (a) The dashed line represents the best-fitting sigmoidal function to the tSTD values across smoothing kernels that was used to interpolate between points; the values of the coefficients of this sigmoid function are provided in the top right corner. The black line and gray shading represent a range of volume smoothing kernels with FWHM between 2.0 and 1.9 mm which, using the sigmoid interpolation function, determines a range of corresponding tSTD values marked with blue shading. A tangential kernel with NB=5, marked with a black circle, has comparable smoothing capacity (tSTD value) to a volume-smoothing kernel with FWHM=2.0 mm. (b) Selected intracortical kernels (from a discrete set of radii) of smoothing capacity comparable to a volume smoothing of FWHM=2.0 mm or slightly smaller. The radial extent of the intracortical kernels is indicated by the color-coded points (blue-to-cyan and red-to-yellow) and a legend is provided at the top of each plot; the gray shading represents a range of volume-smoothing kernels with FWHM between 2.0 and 1.8 mm. For each radial extent one intracortical kernel is selected based on its correspondence to the volume-smoothing kernels from this range, and it is marked with a circle.

Supplementary Fig. 2. Example sagittal slice and axial and coronal reformats of intensity bias-corrected 0.75 mm isotropic resolution anatomical T_1-weighted MEMPRAGE data with cross-sections of cortical surface reconstructions overlaid: the *yellow contour* represents the white matter surface and the *red contour* represents the pial surface. Small errors can be seen in the vicinity of the temporal pole and the orbitofrontal cortex, as previously reported for similar 7T MEMPRAGE data (Zaretskaya et al., 2018), however overall the automatic surface reconstruction quality is high across most of the hemispheres.

Supplementary Fig. 3. Example histograms of vertex spacing (average distance between any given vertex and its immediate neighbors) calculated separately for gyri, sulci and banks, for the white matter surface mesh and for the pial surface mesh, of the left hemisphere of one subject. To consistently identify gyri, sulci and banks between the white and pial surfaces, the gyri, sulci and banks were defined based on the curvature of the midgray surface (50% of the depth) using thresholds of 0.25 and −0.25 mm^{-1} (where curvature values fell into the [−1, 1] range).

Supplementary Fig. 4. tSNR values (averaged across 5 subjects) calculated for 1.1-mm isotropic resting-state fMRI data after smoothing with a set of kernels with equivalent smoothing capacities. For comparison, the resulting tSNR was normalized to reference tSNR of conventional volume-based smoothed data using a 3D kernel with FWHM=2.0 mm sampled at midgray depth. The reference tSNR of the volume-smoothed data, represented by the gray bar, is compared with the tSNR after applying a set of surface-based smoothing kernels with smoothing capacity matched to the FWHM=2.0 mm volume-smoothing kernel: a purely tangential kernel with NB=5 (radius≈3.3 mm, cyan bar) where the resulting tSNR values were averaged across depths, and with intracortical kernels with varying tangential neighborhoods (blue and red bars) including: one extending across all depths (IC-all: 00–10), five extending from the WM to one of the intermediate depths (IC-wm: 00–08, 00–06, 00–04, 00–02, 00), and five centered at midgray depth and extending symmetrically in both directions (IC-mid: 01–09, 02–08, 03–07, 04–06, 05). Kernels IC-wm 00 and IC-mid 05 represent extreme cases consisting of only one cortical surface. Normalized tSNR of non-smoothed 3.0-mm isotropic data was plotted for comparison (white bar). Error bars indicate standard error across subjects.

Supplementary Fig. 5. Normalized z-statistic values (averaged across 5 subjects) calculated for 1.1-mm isotropic BH task fMRI data after smoothing with a set of kernels with equivalent smoothing capacities. The z-statistic values in each subject were first normalized to the z-statistic resulting from conventional volume-based smoothed data using a 3D kernel with FWHM=2.0 mm sampled at midgray depth, then averaged across subjects. The z-statistic of the reference volume-smoothed data, represented by the gray bar, is compared with the z-statistic after applying a set of surface-based smoothing kernels with equivalent smoothing capacity including: a purely tangential kernel with NB=5 (radius≈3.3 mm, cyan bar) where the resulting z-statistic values were averaged across depths, and with intracortical kernels with varying tangential neighborhoods (red bars) including: one extending across all depths (IC-all: 00–10), five extending from the WM to one of the intermediate depths (IC-wm: 00–08, 00–06, 00–04, 00–02, 00), and five centered at midgray depth and extending symmetrically in both directions (IC-mid: 01–09, 02–08, 03–07, 04–06, 05). Kernels IC-wm 00 and IC-mid 05 represent extreme cases consisting of only one cortical surface. Normalized z-statistic of non-smoothed 3.0-mm isotropic data was plotted for comparison (white bar). Error bars indicate standard error across subjects.

Supplementary Fig. 6. A two-dimensional histogram presenting the dependence on cortical thickness of the tSNR gain (ratio) calculated for 1.1 mm isotropic resolution data smoothed with surface-based kernel IC-mid 03–07 NB=4 relative to the same non-smoothed 1.1 mm data (c.f. Fig. 6). The color scale is logarithmic and represents the number of vertices falling into a given bin, and bins have been set to correspond to every 0.5 mm of the cortical thickness and every 1 unit of tSNR ratio. Black contour overlays represent a two-dimensional Gaussian function resulting from fitting a mixture of two Gaussians to the value pairs across all vertices (estimated mixing proportion of 90%) and correspond to values from 0.05 to 0.25, equally spaced every 0.05.

Supplementary Fig. 7. Visualization of the spatial distribution of z-statistic averaged across subjects using the FreeSurfer CVS avg35 atlas space, shown on the inflated surface representation for breath-hold data. **(a)** Normalized z-statistic of the non-smoothed 3.0-mm isotropic resolution data and the 1.1-mm isotropic resolution data after smoothing with surface-based kernel IC-mid 03–07 NB=4. **(b)** z-statistic gain (difference) map showing the functional CNR increase seen in the smoothed 1.1-mm isotropic resolution data using the same kernel from panel (a).

Supplementary Fig. 8. Comparison of tSNR values calculated for ultra-high-resolution 0.8-mm isotropic resting-state fMRI data acquired for one subject, based on an oblique-coronal acquisition centered on the occipital lobe, after smoothing with a set of kernels with equivalent smoothing capacities: proposed *3D intracortical smoothing* or IC-mid 03–07/NB=4 (dark blue), *conventional 2D tangential smoothing* or IC-wm 00/NB=5 (red), and *midgray 2D tangential smoothing* or IC-mid 05/NB=5 (light blue). The tSNR values were normalized to reference tSNR of the conventional 2D surface-based smoothed data (equivalent to the 00/NB=5 kernel, red bar); the tSNR calculated for the original (non-smoothed) data is presented for comparison (yellow bar).

Supplementary Fig. 9. Comparison of smoothing applied to a retinotopic "test pattern" visual stimulus and resulting fMRI activation pattern. **(a)** The stimulus was designed to elicit a 'diamond-shaped' activation on the cortical surface of V1 (left). To generate this activation pattern, the intended shape was warped according to a standard visuotopic mapping model and presented to the subject; in this case two orthogonal stimulus conditions corresponding to the "foreground" and "background" activation patterns (middle and right) were presented. **(b)** The resulting activation pattern, in the form of a map of z-statistic values, showing the activation map resulting from the original non-smoothed data (left) and the activation maps resulting from smoothed with either a IC-mid 03–07/NB=1 kernel, which is restricted to the middle of the gray matter ribbon (middle), or a IC-mid 00–04/NB=1 kernel, which intersects with the white matter (right). All activation maps are visualized on the inflated representation of the cortical surface reconstruction.