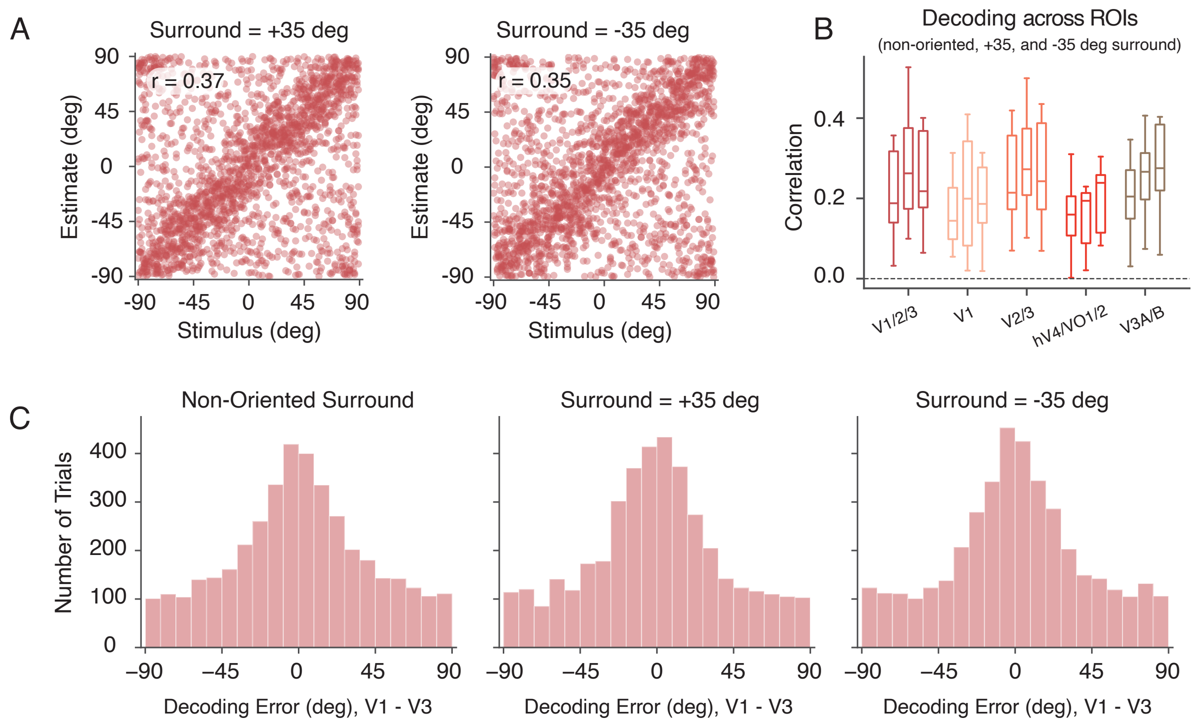
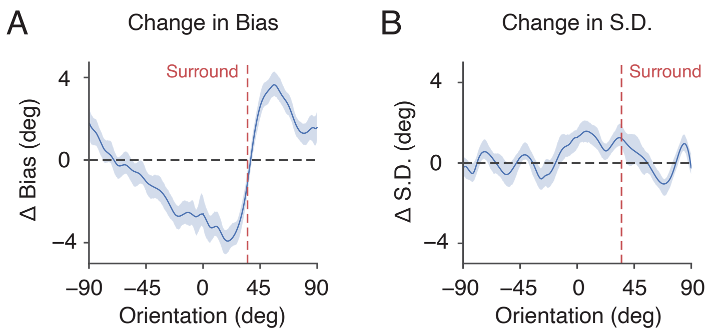
Supplementary Information

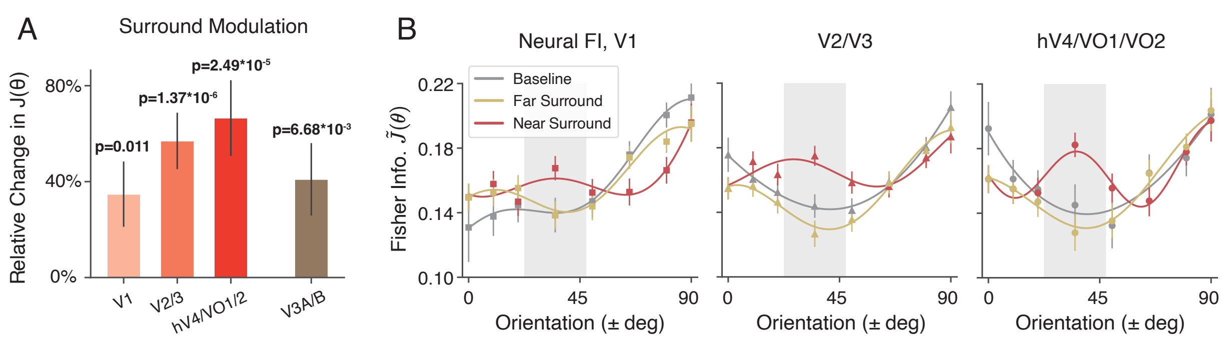
Supplementary figures



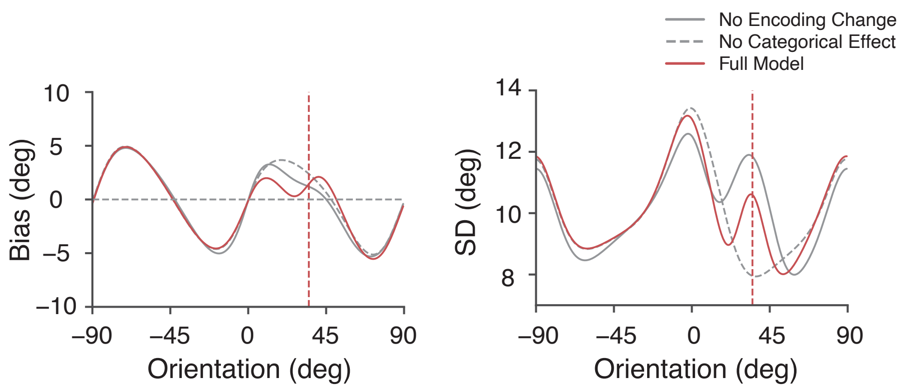
Supplementary Figure 1: Orientation decoding performance. **A)** Same as Fig. 2C, scatter plot of the stimuli orientation (x-axis) versus the decoded orientation (y-axis) from the early visual cortex (V1 to V3), for the two oriented surround ($\pm$ 35) conditions. **B)** Same as Fig. 2D, but with decoding correlation plotted separately for each of the three surround conditions within each ROI. **C)** Histogram of decoding errors from V1 - V3, for the combined subject across the three surround conditions.



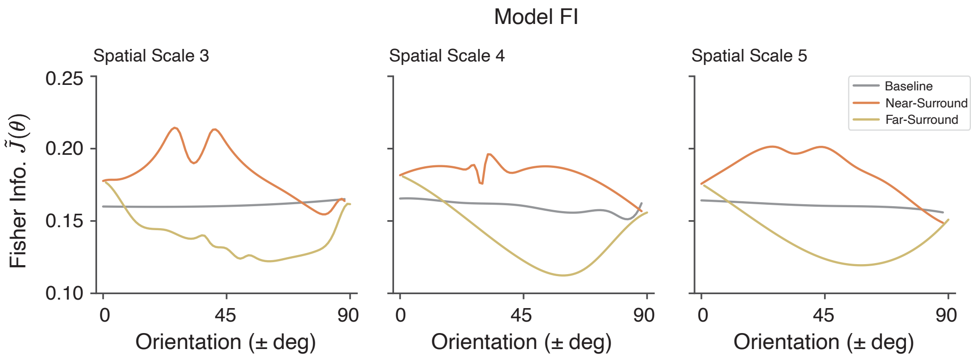
Supplementary Figure 2: Effect of surround modulation on orientation estimation. **A)** Difference in estimation bias between the non-oriented surround and the oriented surround condition. **B)** Difference in the standard deviation of the orientation estimates between the non-oriented surround and the oriented surround condition. The shaded area indicates ±SEM.



Supplementary Figure 3: Neural encoding across visual areas with expanded eccentricity ROI. We repeated the same analysis as in Fig. 4D - E, but expanded the eccentricity selection to between 1 and 15 degrees to cover the entire stimulus. **A)** The relative change in neural FI with respect to the baseline near the surround orientation across different visual cortex ROIs. **B)** Comparison of neural FI along the visual ventral stream, between the near-surround side, far-surround side, and the baseline condition. Error bars indicate ±SEM.



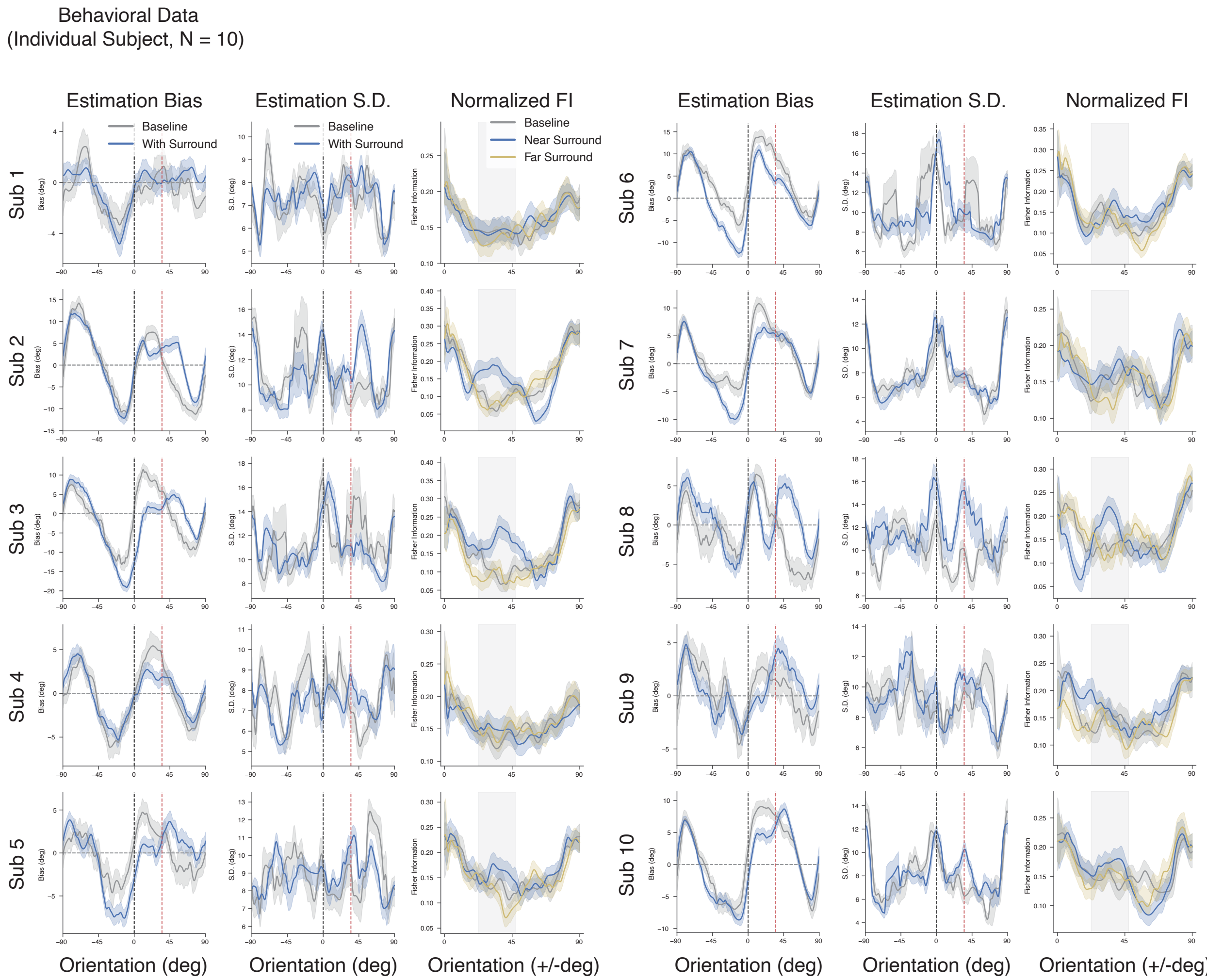
Supplementary Figure 4: Both the dynamic change in sensory encoding and the categorical boundary are necessary for the correct model prediction of the tilt illusion. Panels show the predicted estimation bias and standard deviation of the observer model in the surround condition: Solid gray lines represent the model prediction without assuming a change in sensory encoding (i.e. using the encoding pattern from the baseline condition), while the dashed gray lines represent the model prediction without assuming the categorical boundary at the surround orientation. The solid red lines represent the prediction based on the full model (same as in Fig. 6). Both mechanism are required to correctly predicts the characteristic repulsive bias in the tilt illusion.



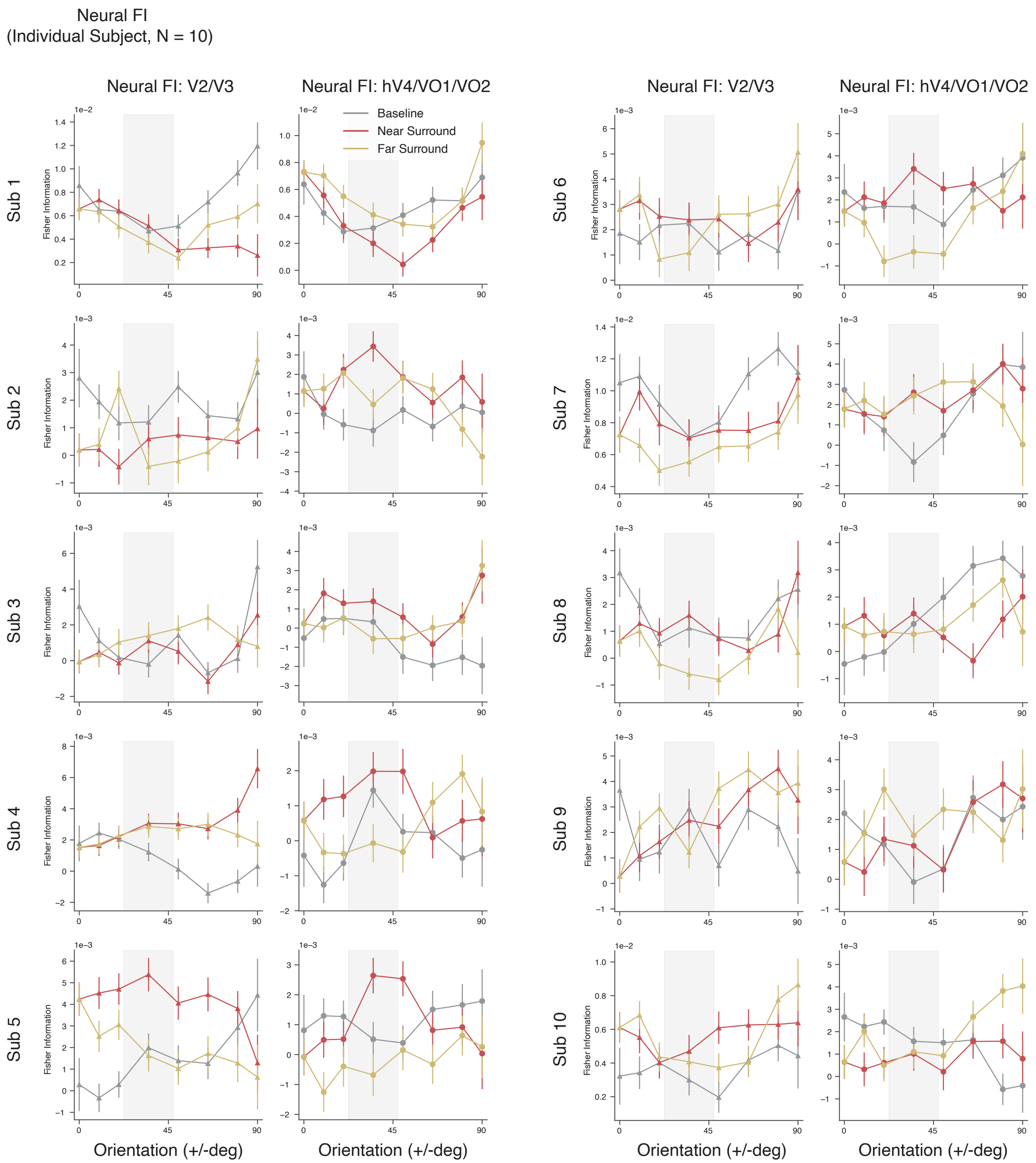
Supplementary Figure 5: The effect of stimulus configuration on encoding FI.

The neural basis of orientation decoding using functional imaging has been the subject of ongoing debate[32,33,74], with recent findings challenging the notion that decoding is based on sensitivity to columnar-level neural tuning. In one sense, our results are independent of the outcome of this debate: Our neural measures of orientation encoding show strong consistency with behavioral data, indicating that regardless of the precise source of the orientation signal, it is indeed utilized by downstream processes and reflected in behavior. Furthermore, there are several notable features in our data that cannot be fully explained by stimulus and aperture configuration (i.e., vignetting) alone. In this analysis, we calculated the encoding FI of the voxel encoding model based on steerable pyramid decomposition at different spatial scales. The model is identical to that shown in Fig. 7A, except the voxel responses are averaged over orientation channels at a single scale. The encoding FIs are qualitatively similar in all cases: flat for the baseline, with a broad increase for near-surround orientations, and a broad decrease for far-surround orientations. There are at least three aspects of our data that are inconsistent with this “vignetting only” model. First, we observed an anisotropy in orientation encoding under the non-oriented surround condition. Given that the stimuli were designed to be isotropic (gray line), this effect must arise from anisotropies inherent in the neural representation of orientation. Second, we found that the effects of stimulus configuration in the oriented surround condition are broad and symmetrical at the surround and orientation orthogonal to it (orange and yellow line), inconsistent with the local changes we observed. Third, the model fails to replicate the increased effects of surround modulation across the visual hierarchy, as the effects of stimulus configuration remain similar across spatial scales. Therefore, while we do not rule out the possibility that stimulus configuration partially contributes to the tilt illusion, additional mechanisms in neural coding are necessary to fully explain our results.

Supplementary data for individual subject



Supplementary Figure 6: Behavioral data for individual subject. The bias, standard deviation of the orientation estimates, and the normalized behavioral FI for individual subject (N=10).



Supplementary Figure 7: Neural FI for individual subject. The unnormalized neural FI from two visual area ROIs (between 1 - 7 degrees for V2/V3 and hV4/VO1/2) for individual subject (N=10).