Modeling shape representation in area V4

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The relative importance of boundary vs. surface features for the neural encoding of objects in the ventral visual pathway remains unclear. Theoretical work has emphasized the need for both types of information, but biologically plausible models attempting to account directly for neuronal responses in V4 have emphasized boundary orientation. To examine this, we manipulated boundary and surface properties of simple shapes to examine their influence on the representation in cortical area V4 in a combined electrophysiology and modeling study. The current best model for V4 shape selectivity is a hierarchical-Max() model that achieves translation invariance and boundary contour tuning similar to that reported in V4. We compared the ability of this model and V4 neurons to maintain their tuning across a large battery of simple shapes that were presented either in filled or outline form. We found that the model, trained only on filled shapes, maintained robust tuning for outlines. Surprisingly, we also found that most V4 neurons did not maintain their shape tuning (as measured with filled shapes) for outlines, with many revealing a complete collapse of tuning (low firing rates to all outline shapes). We retrained the model on shapes and outlines together, and found the model was unable to simultaneously be selective for filled shapes and unselective for their outlines. This indicated that the model is emphasizing orientation patterns that characterize the boundary while discarding phase information relevant to the surface fill. We used these insights to restructure the model, allowing shape-tuned V4 subunits to access phase-dependent inputs from early in the hierarchy, and found that this new architecture could explain the data. Our results suggest that boundary orientation and surface information are both maintained until at least the mid-level visual representation. We hypothesize that this arrangement is crucial for image segmentation.

We have also compared the model to area V4 in terms of other important physiological properties: translation invariance and scale invariance. We find that the existing model does not achieve V4-like levels of invariance, in that shape selectivity changes substantially when stimuli are repositioned within the receptive fields or when size is altered. By manipulating the model and probing its representation at successive levels, we have gained insight into how and where translation and scale invariance breaks down. Important factors include: the normalization equations, the design of the low-level convolutional features, and receptive field density.

In the workshop, I will discuss the equations and architecture of the HMAX model and how it can be altered to account for novel experimental data. I will also discuss how other convolutional and deep networks may be able to generate robust V4-like representations.

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