Contextual interactions in grating plaid configurations are explained by natural image statistics and neural modeling

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The processing and analysis of natural scenes requires the visual system to integrate localized, distributed image features into global, coherent percepts. A central hypothesis states that our brain uses statistical dependencies in visual scenes: when represented in neural interactions between elementary feature detectors, they will enhance the processing of certain feature conjunctions, while suppressing others. As a neural mechanism realizing these modulatory effects, pairwise interactions between feature detectors in early visual areas have been proposed.

By combining psychophysical experiments with computational modeling and image analysis, we investigated which interaction structures underlie feature integration in visual cortex, and how perception and neural interactions relate to natural scene statistics.

As stimuli we used grating patch configurations (plaids) comprising four patches with varying orientations (45° / -45°), spatial frequencies (low / high), and inter-patch distances (1° / 2° of visual angle).

Human detection thresholds for plaids were strongly modulated by inter-patch distance, number of orientation- and frequency-aligned patches and spatial frequency content (low, high, mixed).

Using a structurally simplistic cortical model comprising orientation columns connected by horizontal axons, we were able to reproduce detection thresholds for all configurations quantitatively. The model consists of 4 x 4 neural populations, representing all patch configurations per position. Interaction strengths were initialized randomly and optimized by a stochastic gradient descent. We used two approaches, namely (A) having no restrictions on the weight matrix for allowing a maximum number of degrees of freedom (DOF), and (B) imposing a connection structure mirroring physiological and psychophysical evidence with a small number of DOFs. Both approaches yield similar results: In addition to medium-range inhibition and long-range, orientation-specific excitation, model and experiment predict a novel form of strong orientation-specific, inhibitory interactions between different spatial frequencies.

For large inter-patch distances, detection thresholds for the plaids were inversely related to their likelihood of occurrence in natural images. However, for small inter-patch distances, natural image statistics can not explain psychophysics, hence suggesting a different functional role of the suppressive interactions observed for small inter-patch distances.

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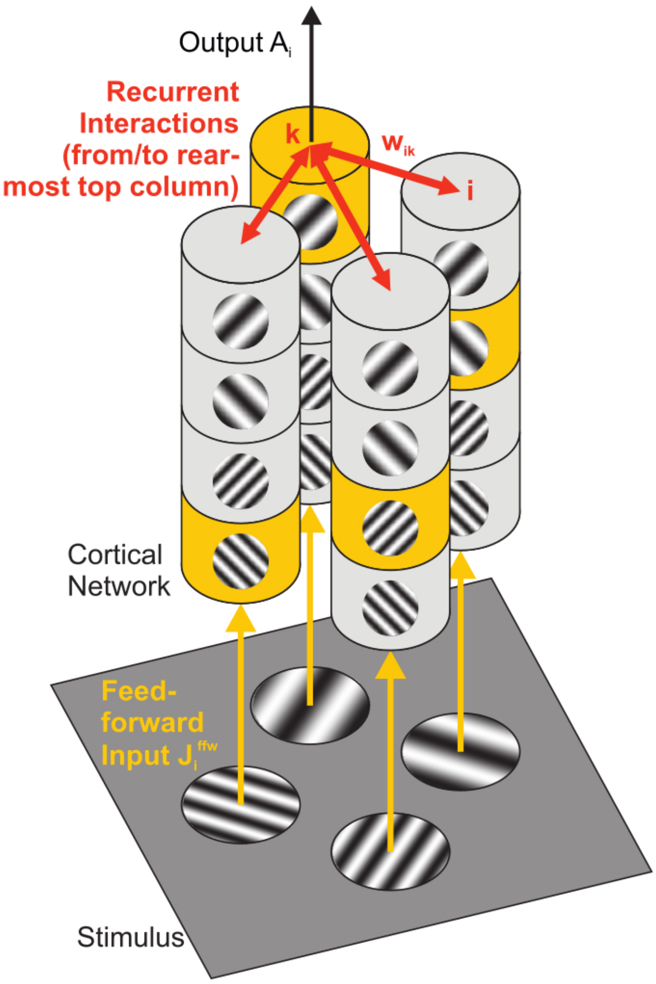

Figure: The four patches in a visual stimulus activate the corresponding neural columns with matching orientations and SF preferences (yellow) in each of the 4 hypercolumns (vertical structures), while horizontal interactions (red) provide recurrent feedback (only part of all connections are shown).