Towards a unified model of classical and extra-classical receptive fields

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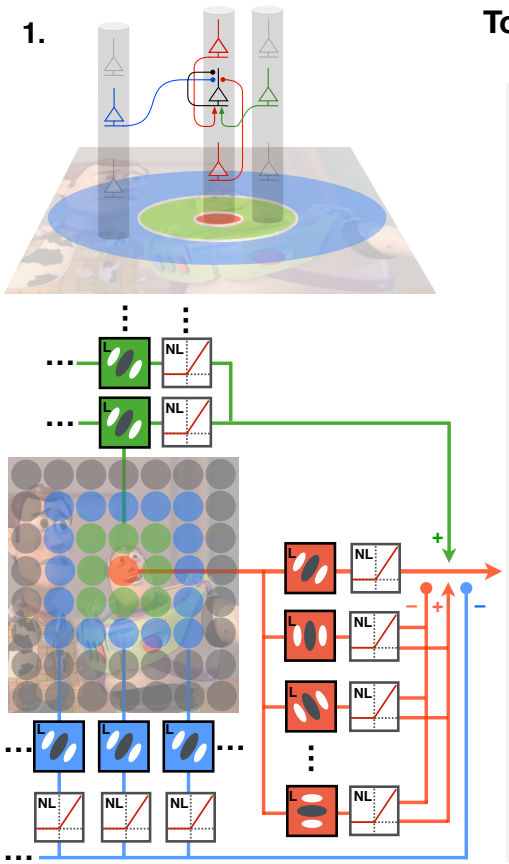
1.



$$\mathbf{Q}^{i,j}_{\theta} = \sum_{\vartheta \in \mathbf{\Theta}} \mathbf{W}_{\theta,\vartheta} \mathbf{X}^{i,j}_{\vartheta}$$

Columnar: broadly tuned excitation
Binzegger et al. 2004; Shushruth et al. 2012; Stepanyants et al. 2008

$$\mathbf{U}^{i,j} = \frac{1}{|\mathbf{\Theta}|} \sum_{\vartheta \in \mathbf{\Theta}} \mathbf{Y}^{i,j}_{\vartheta}$$

Columnar: untuned inhibition
Carandini et al. 1997; Busse et al. 2009; reviewed in Carandini & Heeger 2012

$$\mathbf{T}^{i,j}_{\theta} = \frac{1}{\left|\mathbf{S}^{f}_{i,j}\right|} \sum_{u,v \in \mathbf{S}^{f}_{i,j}} \mathbf{Y}^{u,v}_{\theta}$$

Far surround: tuned inhibition
DeAngelis et al. 1994; Gilbert & Wiesel 1990; Knierim & Van Essen 1992; Seriès et al. 2004

$$\mathbf{P}^{i,j}_{\theta} = \frac{1}{\left|\mathbf{S}^{n}_{i,j}\right|} \sum_{u,v \in \mathbf{S}^{n}_{i,j}} \mathbf{X}^{u,v}_{\theta}$$

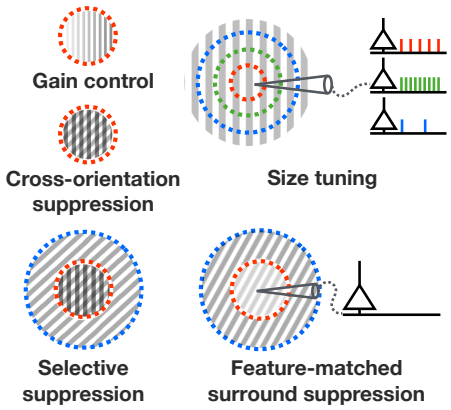
Near surround: tuned excitation
Angelucci & Shushruth 2013; Gilbert & Wiesel 1989

$$\eta \partial_t \mathbf{X}^{i,j}_{\theta} + \varepsilon^2 \mathbf{X}^{i,j}_{\theta} = \left[\xi \mathbf{L}^{i,j}_{\theta} - (\alpha \mathbf{X}^{i,j}_{\theta} + \mu) \mathbf{U}^{i,j} - (\beta \mathbf{X}^{i,j}_{\theta} + \nu) \mathbf{T}^{i,j}_{\theta} \right]_+$$

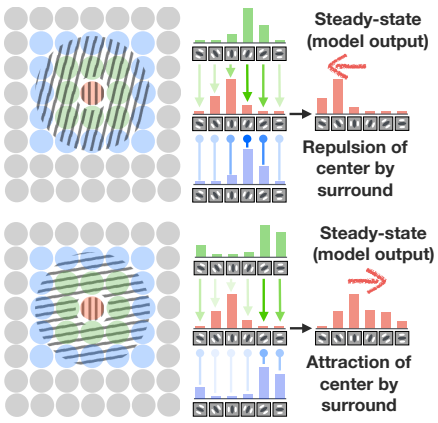
$$\tau \partial_t \mathbf{Y}^{i,j}_{\theta} + \sigma^2 \mathbf{Y}^{i,j}_{\theta} = \left[\zeta \mathbf{X}^{i,j}_{\theta} + \gamma \mathbf{P}^{i,j}_{\theta} + \delta \mathbf{Q}^{i,j}_{\theta} \right]_+$$

1. A neural field model with four distinct patterns of recurrent connections characterizes interactions between hypercolumns (cRF; disks in bottom figure); the model output corresponds to a highly nonlinear steady-state (see **2.**). Top figure: plausible wiring diagram. Equations: **X** and **Y** represent the input and output to a model unit, **θ** its tuning (in this example, orientation) and **i**, **j** the coordinates of the cRF.

2. a.

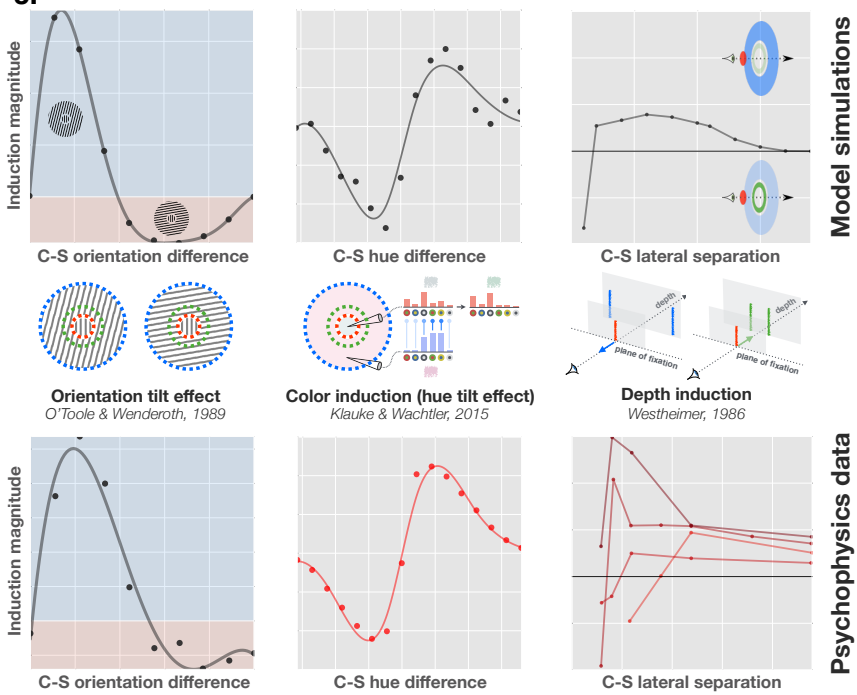


2. b.



2. The model accounts for basic contextual phenomena reported in the primate primary visual cortex (**2. a.**), inside and outside the cRF, with fixed parameter values. The model also accounts for both 'repulsion' (**2. b.**, top) and 'attraction' (**2. b.**, bottom) as reported in the human psychophysics literature on the orientation tilt effect. The model is agnostic about the tuning of the model units it is applied to, and can thus explain contextual phenomena in other visual modalities (see **3.**).

3.



3. The model offers a reinterpretation of induction / tilt effects across visual modalities. This is not trivial because the neural code varies from modality to modality: e.g., a continuous code for orientation, versus a discrete, opponent code for hue, as well as because of variations in the stimuli used: e.g., the orientation tilt effect and color induction use dense stimuli that simultaneously activate antagonist mechanisms, the inhibitory far surround and the excitatory near surround, whereas depth induction uses sparse stimuli that activate those separately. Yet, it is possible to measure biases in the stimulus value encoded by model units ("model simulations") that are commensurate with similar biases in human perception ("psychophysics data", replotted from original papers). The model explains, *without the need for parameter tuning*, that induction phenomena across visual modalities all result from the unequal activation of either kind of extra-cRF surround by the surround stimulus.

Take-away points. A unified model accounts for **1.** primary visual cortex neurophysiology across visual modalities as well as **2.** contextual phenomena, also across visual modalities, as shifts in population responses and **3.** achieves color constancy (not shown), suggesting that it offers a bridge between circuit-level mechanisms and higher-level visual function.