Non-classical receptive field inhibition and its relation to orientation-contrast pop-out and line and contour saliency: a computational approach

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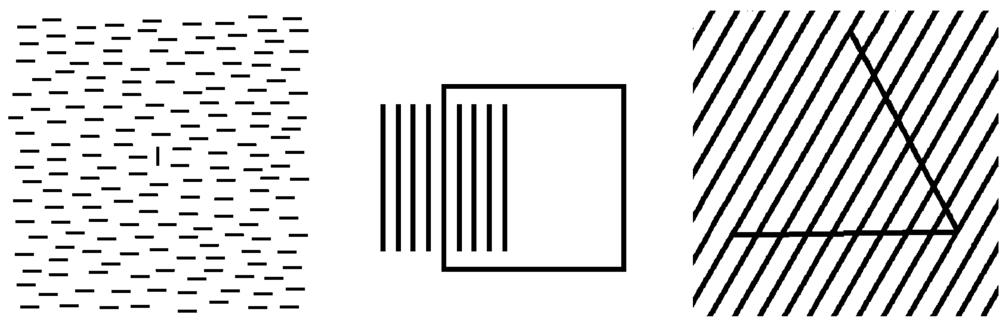
Introduction

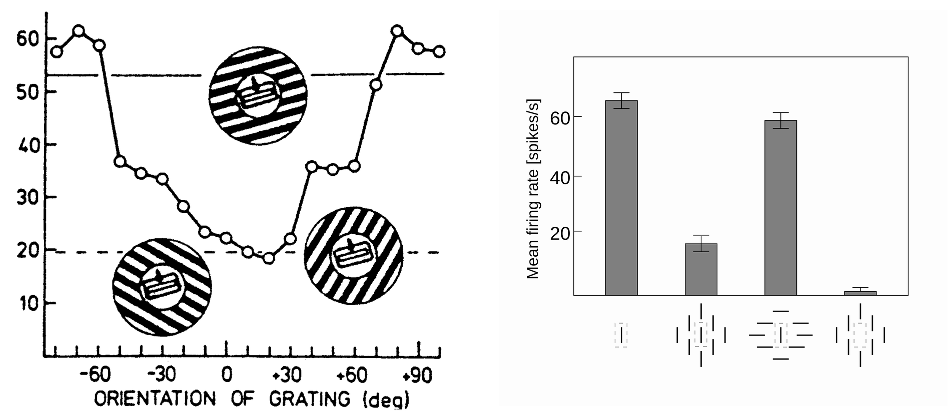
The perception of oriented stimuli depends on the surroundings in which they are embedded, Fig. 1.



(a) (b) (c)

Figure 1: *(a) Orientation contrast pop-out: the vertical stimulus in the center segregates from its surroundings of differently oriented stimuli. (b) A section of the contour of the rectangle is 'lost' in the grating. (c) The three legs of the triangle are perceived differently.*

These perceptual effects are related to a neural mechanism known as *non-classical receptive field (non-CRF) inhibition* or *surround suppression*. Its essence is that the response of an orientation selective neuron (in V1 or V2) to an optimal stimulus in its CRF is modulated, most commonly inhibited, by other stimuli outside the CRF, Fig. 2. For 24% of the cells, surround stimuli of the same orientation as the main stimulus over the CRF have stronger suppression effect than stimuli of other orientations [3]. We refer to this type of modulation as *anisotropic inhibition*.



(a) (b)

Figure 2: *(a) Response of a neuron to a stimulus composed of a single bar of optimal orientation in the CRF (central circle) and a grating of varying orientation outside the CRF [1]. The inhibition by the surrounding grating is strongest when its orientation coincides with the orientation of the optimal stimulus. (b) Responses of a visual neuron to various stimuli (from left to right): a single bar of optimal size and orientation inside the CRF (delineated by a dotted rectangle), an optimal bar stimulus in the CRF surrounded by other bars of the same orientation outside the CRF, an optimal bar in the CRF surrounded by bars of orthogonal orientation, no optimal stimulus in the CRF [3].*

Computational model

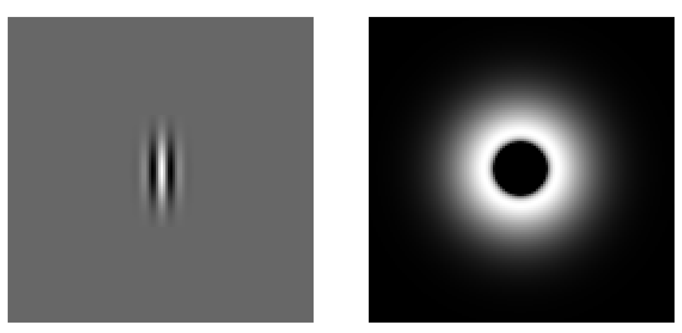
Simple cell

We model CRFs of simple cells by Gabor functions (Fig. 3a):

$$g_{\lambda,\sigma,\theta,\varphi}(x,y) = e^{-\frac{\tilde{x}^2+\gamma^2\tilde{y}^2}{2\sigma^2}}\cos(2\pi\frac{\tilde{x}}{\lambda}+\varphi)$$
$$\tilde{x} = x\cos\theta + y\sin\theta, \qquad \tilde{y} = -x\sin\theta + y\cos\theta,$$

where γ is the spatial aspect ratio, σ determines the size of the receptive field, λ is the preferred wavelength, θ is the preferred orientation, and φ determines the symmetry.
The response of a simple cell CRF to a stimulus $f(x,y)$ is computed by convolution, i.e. summation of $f(x,y)$ over the CRF, weighted by $g_{\lambda,\sigma,\theta,\varphi}(x,y)$:

$$r_{\lambda,\sigma,\theta,\varphi}(x,y) = (f * g_{\lambda,\sigma,\theta,\varphi})(x,y)$$



(a) (b)

Figure 3: *Intensity maps of (a) a Gabor function $g_{\lambda,\sigma,\theta,\varphi}(x,y)$ modelling a CRF and (b) a weighting function $w_\sigma(x,y)$ modelling the inhibition surround of that CRF.*

Complex cell

The response of a complex cell is computed from the responses of a pair of simple cells with a phase difference of $\frac{\pi}{2}$ (see Fig. 4 for an example):

$$E_{\lambda,\sigma,\theta}(x,y) = \sqrt{r^2_{\lambda,\sigma,\theta,0}(x,y) + r^2_{\lambda,\sigma,\theta,-\frac{\pi}{2}}(x,y)}.$$

(a) (b) (c) (d)

Figure 4: *(a) An input image. (b-c) Computed responses of complex cells with (b) vertical and (c) horizontal preferred orientation. (d) The maximal responses across all orientations.*

Non-CRF inhibition

In [4] we define a weighting function $w_\sigma(x,y)$ on an annular area surrounding the CRF (Fig. 3b),

$$w_\sigma(x,y) = \frac{1}{||H(\text{DoG}_\sigma)||_1}H(\text{DoG}_\sigma(x,y)),$$
$$H(z) = \begin{cases} 0 & z < 0 \\ z & z \geq 0, \end{cases}$$
$$\text{DoG}_\sigma(x,y) = \frac{1}{2\pi(4\sigma)^2}e^{-\frac{x^2+y^2}{2(4\sigma)^2}} - \frac{1}{2\pi\sigma^2}e^{-\frac{x^2+y^2}{2\sigma^2}},$$

and compute an inhibition term by weighted summation (over the annular area) of the responses of complex cells with a given preferred orientation θ, wavelength λ and CRF size σ:

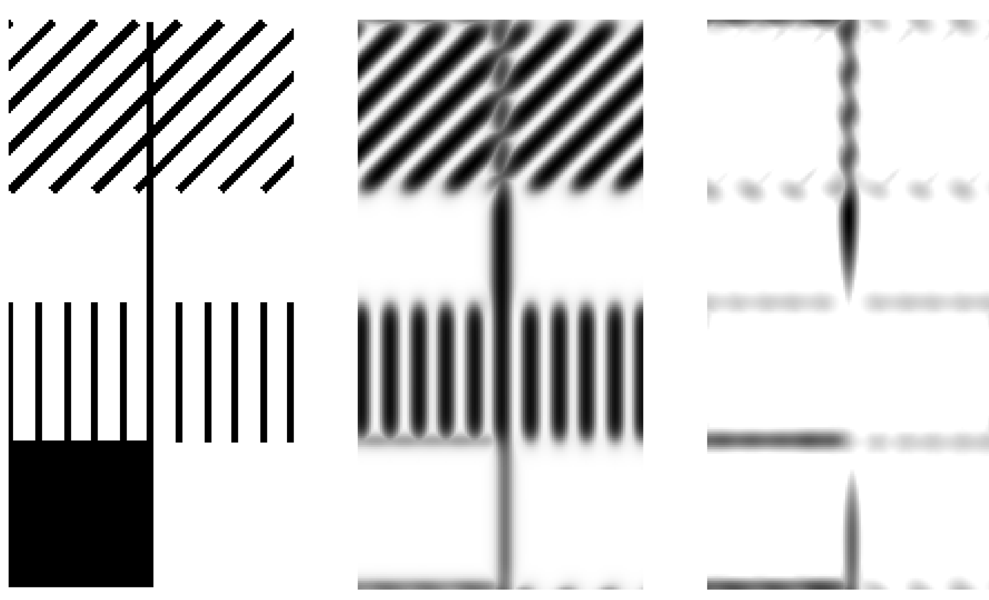
$$t^A_{\lambda,\sigma,\theta}(x,y) = (E_{\lambda,\sigma,\theta} * w_\sigma)(x,y).$$

The response of a complex cell with anisotropic surround inhibition is computed as the half-wave rectified difference of the response of that cell to the stimulus in the CRF $E_{\lambda,\sigma,\theta}(x,y)$ and the inhibition term $t^A_{\lambda,\sigma,\theta}(x,y)$:

$$\tilde{b}^{A,\alpha}_{\lambda,\sigma,\theta_i}(x,y) = H(E_{\lambda,\sigma,\theta}(x,y) - \alpha t^A_{\lambda,\sigma,\theta}(x,y)).$$

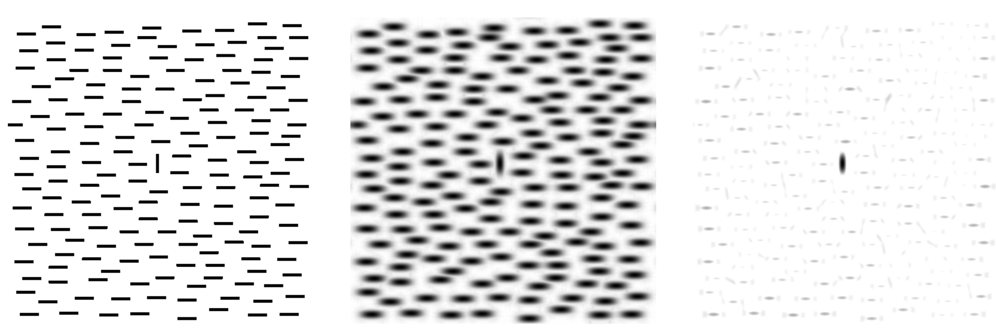
The factor α controls the strength of the inhibition.

Results of computational experiments



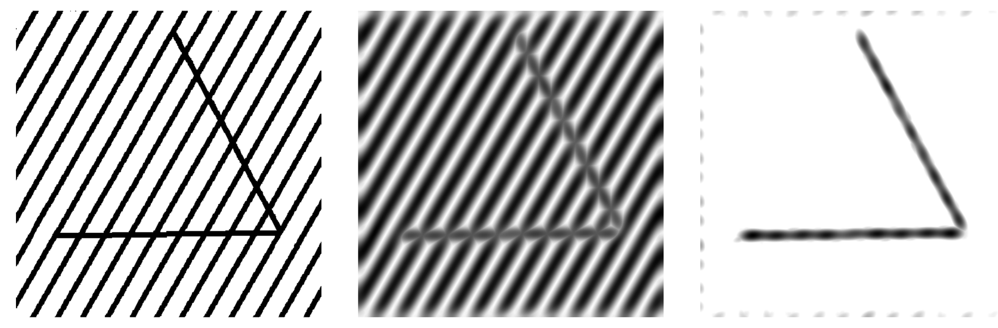
stimulus | CRF responses | surround inhibited responses

Figure 5: *(left) Synthetic stimulus. (middle) All lines and edges are enhanced in the CRF responses. (right) The surround inhibited responses to texture edges are weak, single lines and edges are enhanced.*



stimulus | CRF responses | surround inhibited responses

Figure 6: *Stimulus and computed responses. The surround inhibited responses (right) mimic the orientation-contrast pop-out effect: the response to the single vertical bar is stronger than the responses to the texture of horizontal bars.*



stimulus | CRF responses | surround inhibited responses

Figure 7: *Gali-Zama triangle stimulus and computed responses. The two legs of the triangle which are not parallel to the grating give rise to stronger responses in the surround inhibited channel (right) than the third leg.*

stimulus | CRF responses | surround inhibited responses

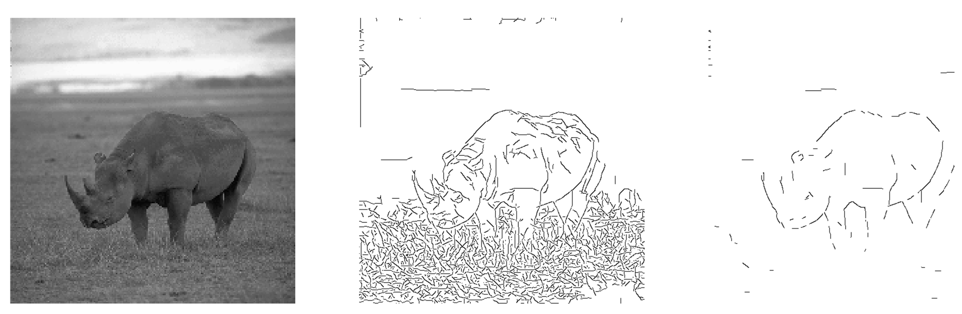
Figure 8: *Kanizsa rectangle stimulus and computed responses. In the surround inhibited channel (right), the response to the part of the rectangle that is embedded in the grating is weaker.*

Conclusions

Computer simulations confirm that non-CRF inhibition is the possible origin of:

- orientation-contrast pop-out
- reduced saliency of lines/contours embedded in gratings

Further computational experiments suggest that the biological utility of non-CRF inhibition is the separation of contour from texture information and mediation of object contours to higher cortical areas [2], Fig. 9.



stimulus | CRF responses | surround inhibited responses

Figure 9: *(left) Natural image stimulus. (middle) The CRF responses to texture and contours are equally strong. (right) The surround inhibited responses enhance mainly contours.*

References

[1] C. Blakemore and E. A. Tobin. Lateral inhibition between orientation detectors in the cat's visual cortex. *Exp. Brain Res.*, 15:439–440, 1972.

[2] C. Grigorescu, N. Petkov, and M. A. Westenberg. Contour detection based on nonclassical receptive field inhibition. *IEEE Trans. Image Processing*, 12(7):729–739, 2003.

[3] H. C. Nothdurft, J. L. Gallant, and D. C. van Essen. Response modulation by texture surround in primate area V1: Correlates of "popout" under anesthesia. *Vis. Neurosci.*, 16:15–34, 1999.

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