TiViPE Simulation of a Cortical Crossing Cell Model

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Abstract. Many cells in cat and monkey visual cortex (area V1 and area 17) respond to gratings and bar patterns of different orientation between center and surround [18]. It has been shown that these cells respond on average 3.3 times stronger to a crossing pattern than to a single bar [16]. In this paper a computational model for a group of neurons that respond solely to crossing patterns is proposed, and has been implemented in visual programming environment TiViPE [10]. Simulations show that the operator responds very accurately to crossing patterns that have an angular difference between 2 bars of 40 degrees or more, the operator responds appropriately to bar widths that are bound by 50 to 200 percent of the preferred bar width and is insensitive to non-uniform illumination conditions, which appear to be consistent with the experimental results.

1 Introduction

Neurons in the primary visual cortex (V1) respond in well defined ways to stimuli within their classical receptive field (CRF), but these responses can be modified by stimuli overlying the surrounding area. This non classical surround provides input from a larger portion of the visual scene than originally thought, permitting integration of information at early levels in the visual processing stream. Recent works indicate that neuronal surround modulation at cross-orientation, an orientation orthogonal to the preferred orientation of the CRF, play a key role in intermediate-level visual tasks, such as perceptual pop-out [14], contrast facilitation [3, 20], and contextual modulation [8, 4, 5], and could endow neurons with a graded specialization for processing angular visual features such as corners and junctions [18, 4].

Neuronal output activity was enhanced in both cat and macaque primary visual cortex (V1) when a surrounding field at a significantly different orientation (30 degrees or more) was added to the preferred orientation of the CRF [18]. The response of these neurons to line crossings at different angles have been described more extensively by [15, 17, 16]. They reported that more than 30 percent of the

neurons studied in the cat striate cortex (area 17) had a significant increase in response (by 3.3 times on average) under stimulation of two crossing bars of distinctive preferred orientation as compared to a single bar.

Many of the cells found so far are cross-orientation selective, and respond vigorously to patterns that contain a different orientation between center (CRF) and non-classical surround. However, most of these cells also respond to a single bar or grating pattern of one orientation. Neuronal cells with a graded specialization for crossing type of junctions, will be modeled in this paper. The constructed operator will be termed *crossing cell operator*.

The paper is organized as follows: In Section 2 the crossing cell operator will be constructed and its properties evaluated. Section 3 the experimental setup will be presented and results of the operator in a real world environment under different non-uniform illumination conditions will be demonstrated. The paper finishes with a discussion.

2   Crossing Cells

Recent reports [18, 16, 3, 7] have demonstrated that the responsiveness of neurons in V1 is modulated by stimuli placed outside their CRFs. Cells with suppressive surround influence corresponding to surround orientation of a grating or bar pattern at the neuron's preferred orientation were found. The responses of these cells were roughly sinusoidal to sigmoidal increasing when the surround orientation was modified, reaching the strongest response when it was perpendicular to the preferred orientation of the CRF. We believe that crossing cells, which have a graded specialization for crossing type of junction of neurons, belong to this group of of neurons.

2.1   Crossing Cell Operator

The complex cell operator responds strongly to a bar or an edge of a preferred frequency, but its response decreases at line ends, junctions and crossings. Since its response is weak at crossings, a subunit is modeled with a center-off response and a surround-on response, as suggested by [1, 18], for a single preferred orientation θ:

$$\mathbf{O}_{\sigma,\theta}(x,y) = w_o\left(\mathcal{C}_{\sigma,\theta}(x_2,y_2) + \mathcal{C}_{\sigma,\theta}(x_3,y_3) - (\mathcal{C}_{\sigma,\theta}(x,y))\right)\ ,\qquad(1)$$

where $x_2 = x + d\sigma\sin\theta$, $y_2 = y - d\sigma\cos\theta$, $x_3 = x - d\sigma\sin\theta$, $y_3 = y + d\sigma\cos\theta$, $d = 8/\sqrt{5}$, $w_o = 2$, σ represents the scale, and θ the preferred orientation. Details of complex cell operator $\mathcal{C}_{\sigma,\theta}$ can be found in [9, 11].

A crossing with preferred orientations θ and $\theta + \varphi$ is modeled to a computational subunit by taking the minimum of the two units and the amplified complex cell responses:

$$\widehat{\mathbf{X}}_{\sigma,\theta,\varphi} = \min\left(\mathbf{O}_{\sigma,\theta}, \mathbf{O}_{\sigma,\theta+\varphi}, 2w_o\mathcal{C}_{\sigma,\theta}, 2w_o\mathcal{C}_{\sigma,\theta+\varphi}\right).\qquad(2)$$

It denotes that such a subunit responds only when there are strong flanked responses ($\mathbf{O}$) and strong center responses ($\mathcal{C}$). Since the strongest response was

found at an orientation that is perpendicular to the preferred orientation, φ is set to 90 degrees. This is in analogy with the orientation difference between center and non-classical surround [7].

The crossing cell model, should respond solely to crossing patterns, hence every response other than at crossing position (x, y) is a false response and must be eliminated. In analogy with the model for endstopped cells [19] this is done by a tangential and a radial inhibition operator, correspondingly:

$$\mathcal{I}_\sigma^t(x, y) = \sum_{i=0}^{2N-1} [\mathcal{C}_{\sigma,\theta_i}(x_4, y_4) - \mathcal{C}_{\sigma,\theta_i}(x, y)]^{\geq 0} \tag{3}$$

and

$$\mathcal{I}_\sigma^r(x, y) = \sum_{i=0}^{2N-1} \left[\mathcal{C}_{\sigma,\theta_i}(x, y) - w_r \mathcal{C}_{\sigma,\theta_{i+N/2}}(x, y) \right]^{\geq 0} , \tag{4}$$

where $x_4 = x + d\sigma \cos\theta_i$, $y_4 = y + d\sigma \sin\theta_i$, $[z]^{\geq 0}$ is equal to 0 for negative z and equal to z elsewhere (half-wave rectification), and constant $w_r = 4$.

The crossing operator at a single scale and a single orientation is:

$$\mathbf{X}_{\sigma,\theta_i} = \left[\left[\widehat{\mathbf{X}}_{\sigma,\theta_i} \right]^{\geq 0} - \frac{g}{N}(\mathcal{I}_\sigma^t + \mathcal{I}_\sigma^r) \right]^{\geq 0} , \tag{5}$$

where g is a gain factor. An appropriate value is $g = 1$, which is used in all experiments.

Finally, a weighted summation is made to obtain appropriate spatial properties:

$$\mathcal{X}_{\sigma,\theta,\varphi} = \mathbf{X}_{\sigma,\theta,\varphi} * G_\sigma , \tag{6}$$

where $G_\sigma(x, y) = 1/(2\pi\sigma^2) \exp(-(x^2+y^2)/(2\sigma^2))$ is a two-dimensional Gaussian function, to yield the crossing cell operator.

2.2   Properties of Crossing Cells

Figure 1 demonstrates desired responses to crossings that have a minimum angle between the two bars of 45 degrees or larger. Due to normalization there appear to be false responses at Figure 1d and f, but these responses are very small, and can therefore be neglected. The response strength to different angles is illustrated in Figure 2a. The response curve shows a relatively strong decrease in when decreasing the angle between the two bars. A half maximum response is found at an angle of around 62 degrees. Responses vanishes when the angle is smaller than 40 degrees. Figure 2a show that at least 32 orientations are needed to obtain a smooth sigmoidal response curve when changing the angle between the two bars, while Figure 2b illustrates that this number of orientations yields little fluctuation in response when rotating the input stimulus.

Figure 2c illustrates that a half-maximum response is at 55 and 180% from the preferred bar width. The crossing operator responds accurately to crossings at 50 and 200 percent of the preferred bar width, as illustrated in Figure 1i and j, but shows artefacts to bars that have a width that is more than twice the preferred bar width (Figure 1k and l).
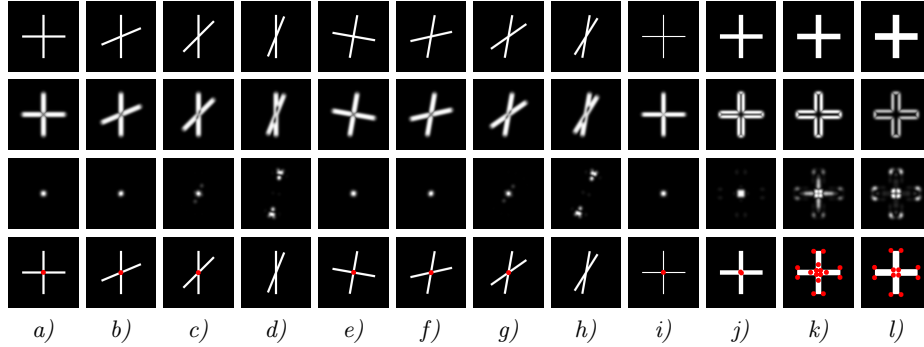
Fig. 1. Responses of the crossing cell operator (6) to crossing patterns of different orientation, and bar width. First to fourth row represent input images, complex cell responses, crossing cell responses, and marked crossings, respectively. For better visualization the results of both complex and crossing cell responses have been normalized. *(a-d)* are the responses to a crossings with a minimum angle between the two bars of 90, 67.5, 45, and 22.5 degrees. *(e-h)* are like (a-d), but the overall pattern has been rotated by 10 degrees. *(i-l)* are like (a), but the bar widths have been set to 4, 16, 20, and 24 instead of 8 pixels. In the simulation the following parameters settings have been used: $N = 32$ orientations, $\sigma = 5.65$ giving the strongest stimulus to a bar width of 8 pixels, and $\lambda = \gamma = 1$
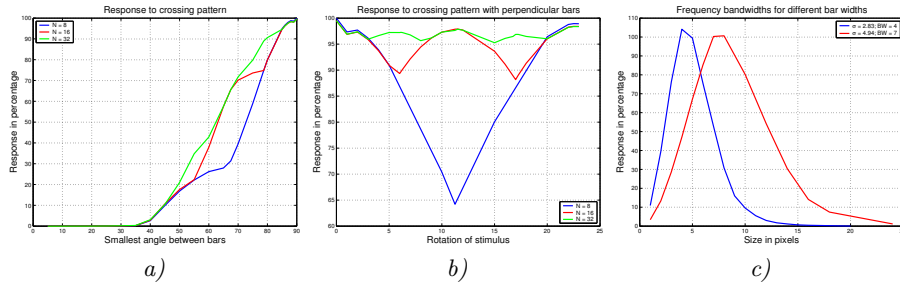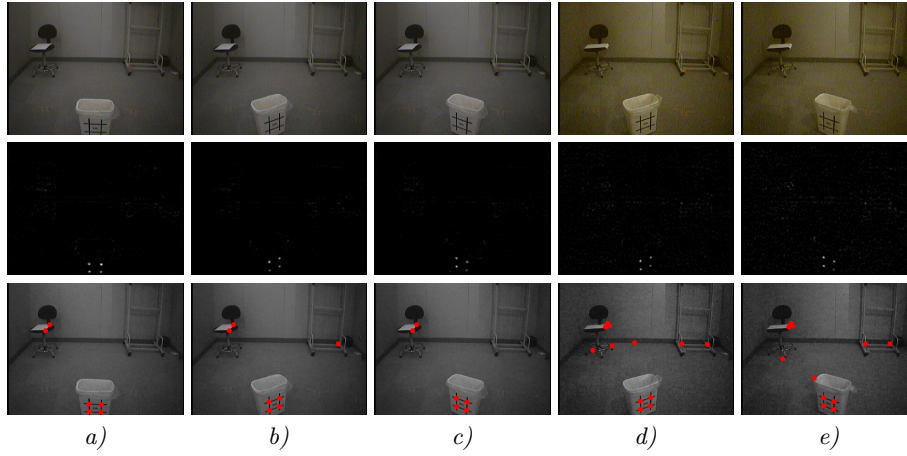

Fig. 2. Responses to crossing pattern. *(a)* Response to different angles (measured in degrees) between two bars, where one preferred orientation is a vertical bar. *(b)* Response to rotation of the whole pattern with perpendicular bars. *(c)* Spatial frequency profiles for different preferred bar widths (BW = 4 and 7 pixels)

3   Crossing Cell Simulation

The crossing cell operator is used in a simulation environment called TiViPE [10], which is explained in more detail below. In the simulation environment, the crossing cell operator has been applied to natural images with different illumination conditions, where an object containing a sharp (#) mark is placed at different distances under different angles. The aim of this simulation is to confirm the results found for the test stimuli. In addition the robustness against irregular

Fig. 3. Experimental setup of crossing cells

illumination conditions is evaluated. The latter is essential in a humanoid robot that operates in a real world environment.

3.1   Experimental Setup

Figure 3 illustrates the experimental setup of the crossing cell operator in TiViPE. The four top-left icons (green) generate a synthetic image, as illustrated in the first row of Figure 1. For natural images the "ReadImage" icon followed by the "RGBtoGrayscale" icon is used instead. The four "Display" icons (yellow) from top to bottom result in input image (stimulus), complex response, crossing response, and marked crossing, respectively, and has been used to generate the results of Figure 1 and 4.

3.2   Crossing Cell Responses to Natural Images

In the simulation color images in VGA format (640x480 pixels) were used as input stimuli. A bucket was placed at distances of 1, 1.5, 2, and 2.5 meters at angles of -60, -30, 0, 30, and 60 degrees, under 3 different (normal, left side dimmed, right side dimmed) illumination conditions yielding a total of 60 different images, which were applied to the crossing operator (6).

All four crossing points of the sharp (#) on the bucket were determined with high accuracy for all distances and orientations of 0 and ±30 degrees, under all

a)   b)   c)   d)   e)

Fig. 4. Responses of the crossing cell operator (6) to real world images with different illumination conditions. **First row** Input stimuli. *(a-c)* Normal light conditions, *(d-e)* Use of light bulbs where lights have been dimmed on the left side, resulting in a shadow on the left side of the bucket. **Second row** Normalized crossing responses applied obtained from the respective input stimuli. **Third row** Marked crossings overlayed on the monochrome input image. The threshold to mark local maxima at crossings was set to 7, where the response of the operator is between 0 and 255. In the simulation the following parameters settings have been used: $N = 8$ orientations, $\sigma = 1.77$ giving the strongest stimulus to a bar width of 2.5 pixels, and $\lambda = \gamma = 1$

3 illumination conditions, using a single scale only ($\sigma = 1.77$). The operator is not responding when the bucket is placed under an angle of ± 60 degrees. This result is expected, since the operator failed to respond to the artificial stimuli with similar angle, see Figure 1d and f.

4   Discussion

Many neurons in primary visual cortex (V1) respond differently to a simple visual element present in isolation, compared to when it is embedded in a more complex stimulus. The difference is in the modulation by surrounding elements, hence it could tune neurons to a graded specialization for processing junctions [18, 4].

Typically the surround influence was suppressive when the surround grating was at the neuron's preferred orientation [3], but when the orientation in the surround was perpendicular to the preferred orientation facilitation became evident. Neural responses to crossings were on average more than 3 times stronger [16], but they also respond to a grating or a single bar of a preferred orientation [18, 16, 3, 7]. These neurons are therefore not specialized to purely respond to junctions. In the monkey, the majority of cells showed response suppression

with increasing grating patch diameter [2, 18], hence it is likely that a group of these neurons respond solely to junctions, crossings in particular. Another possibility is that neurons in adjacent areas use these responses for further processing that accounts for responses to crossings only. Tangential and a radial inhibition operators were used in our model, yielding the proposed "cortical crossing cell" operator.

The operator is robust to different illumination conditions, and responded accurately to crossing patterns at a wide (± 40 degree) angle and at a wide range of scales (50 to 200 percent of the preferred bar width). However, the operator failed at crossings where the smallest angle between a pair of bars was less than four degrees and showed false responses to crossing patterns where the bar width is larger than twice the preferred bar width.

Crossing cells are expected to play a complementary role to endstopped cells which respond to line ends, corners, and junctions, but not to crossings [6, 9]. However, from functional brain modeling perspective, it is desirable to model all junction types [12]. Junctions strongly reduce the amount of visual information and likely play an important role in object recognition. These junctions can be represented as vertices in graphs and be used for symbolic reasoning [13].

The proposed model is developed as part of a larger parallel early vision system, that includes several early vision operators, grouping, attention, and learning mechanisms. The TiViPE environment serves as an integration tool for these operators and mechanisms.

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