The computational model for border-ownership determination consisting of surrounding suppression and facilitation in early vision

Haruka Nishimura[1)] and Ko Sakai[2)],

Graduate School of Systems and Information Engineering, University of Tsukuba,

1-1-1 Tennodai, Tsukuba 305-8573, Japan

haruka@viplab.is.tsukuba.ac.jp[1)], sakai@cs.tsukuba.ac.jp[2)]

Abstract

We have proposed the computational model for border-ownership (BO) determination based on the contrast configurations within a certain range that extends beyond the classical receptive field (CRF). In this study, we adopt two crucial functions of the surrounding modulation reported by the recent physiological studies; (1) changes in functional connection depending on the amplitude of contrast, and (2) a variety of surrounding suppression/facilitation depending on the orientation and retinotopic position of surrounding stimuli relative to the CRF. Simulation results show that the model reproduces the major characteristics of BO selective neurons.

Keywords: border-ownership, contrast, surrounding suppression/facilitation

1. Introduction

The discrimination of figure/ground is the essence for the perception of surface that is the fundamental source for the recognition of visual images such as shape, spatial structure, and motion [1]. It

has been reported that a majority of neurons in monkeys' V2 and V4 showed the selectivity to the direction of figure; their response depends on which side of a border owns the border (BO selectivity) [7]. Recent physiological findings led us to propose two hypotheses for the BO determination in the visual system: (1) contrast information is the basis for BO selectivity: around 70% of BO selective neurons have co-selectivity to contrast [7], and (2) the surrounding suppression/facilitation reported in the striate cortex [6] plays a crucial role to integrate surrounding contrast information. The response of neurons is changed depending on the both retinotopic position and the orientation of surrounding stimuli, both relative to the CRF, which is called contextual modulation that is crucial to realize BO selectivity. Physiological studies have shown that such modulation, which is represented in surrounding suppression/facilitation profiles [2], changes dramatically depending on the magnitude of contrast [4]. Under low-contrast conditions, surrounding suppression is evoked by surrounding stimuli with any orientations, and facilitation is evoked by those with the same orientation as the preferred orientation of the cell. For high-contrast conditions, the nature of modulation is reversed: surrounding suppression is apparent for surrounding stimuli with the same orientations, and facilitation is observed for those with other orientations. It has been further reported that the modulation is generally asymmetrical in retinotopic space [6]. We propose, based on computational studies, that the surrounding contrast is crucial for BO determination, and that surrounding suppression/facilitation is fundamental for the major characteristics of BO selective neurons. Since we modeled a low-contrast condition in the previous report [3], we here present the model for a high-contrast

condition in order to show that the BO could be determined for the both conditions by the identical principle.

2. The model

Our network model consists of four major stages, (1) detection of contrast by V1 simple-cell-like model-neuron [5], (2) integration of surrounding contrast by the mechanism of surrounding suppression/facilitation apparent in V1, (3) realization of the selectivity to BO and contrast, and (4) achievement of the selectivity only to BO of V2 and V4 neurons.

In the first stage, each model neuron has odd-symmetric Gabor filter as CRF, and takes the convolution of an input stimulus with the Gabor masks. The output of this stage is given by

$$O_o^1(x, y) = (S_0 * G_o)(x, y)$$

S_0 is a sub-region of an input stimulus S within a spatial neighborhood of an arbitrary spatial position (x, y). Subscript o represents the preferred orientation. G_o is the Gabor mask for convolution ($*$) and the masks have a variety in orientation (fig. 1); G_0 (bright-dark along the horizontal orientation from the left to right), G_{180} (dark-bright along the horizontal orientation), G_{90} (bright-dark along the vertical orientation from the bottom to top), and G_{270} (dark-bright along the vertical orientation)[5]. In the second stage, the surrounding suppression/facilitation are realized by the surrounding inhibitory/excitatory connections, respectively, from the model-neurons in the first stage. We introduce two spatial constraints to surrounding connections (fig. 2): (1) the excitatory connections exist between the BO-selective model-

neuron and the model neurons in the first stage with contrast selectivity orthogonal to that of BO-selective model-neuron, and the inhibitory connections exit between the BO-selective model-neuron and the model neurons in the first stage with the same preferred orientations [2], (2) the excitatory region extends to the direction that corresponds to the BO preference of the model neuron, and the inhibitory region extends to the opposite direction. The output of the model neurons in the second stage is given by

$$O^2_{(o)ij}(x,y) = (c_i E_i * O^1_{cross})(x,y) - (c_j I_j * O^1_{iso})(x,y),$$

where $O^1_{cross}(x,y) = O^1_{o+90}(x,y) + O^1_{o+270}(x,y)$, $O^1_{iso}(x,y) = O^1_{o}(x,y) + O^1_{o+180}(x,y)$

E_i and I_j are excitatory and inhibitory regions, respectively, and c represents a connection strength. $O^1_{cross}(x,y)$ is the contrast information of cross-orientations and $O^1_{iso}(x,y)$ is that of iso-orientations. In the third stage, model neurons complete the contextual modulation of the response from CRF by taking into account surrounding context computed in the previous stage, which realize the co-selectivity to BO and contrast. The response of the model neurons in this stage is given by

$$O^3_{(o)ij}(x_0,y_0) = O^1_o(x_0,y_0) - (O^1_o(x_0,y_0) + O^2_{(o)ij}(x_0,y_0)), \text{ If } O^1_o(x_0,y_0) > O^2_{(o)ij}(x_0,y_0), \text{ otherwise } O^3_{(o)ij}(x_0,y_0) = 0$$

The contrast selectivity of the model-neurons in the third stage depends on $O^1_o(x_0,y_0)$ that is contrast information of the CRF at (x_0,y_0). BO selectivity of these neurons is determined by $O^2_{(o)ij}(x_0,y_0)$. In the last stage, contrast-independent BO-selective neurons are realized by taking the summation of the activities between a pair of the model neurons in the third stage with the opposite contrast selectivity (fig. 3). The output of model neurons in the fourth stage is thus given by

$$O^4_{ij}(x_0, y_0) = O^3_{(o)kl}(x_0, y_0) + O^3_{(o+180)mn}(x_0, y_0)$$

A variety of the selectivity to BO and contrast reported physiologically was reproduced by the variations of surrounding connections, the spatial arrangement of excitatory and inhibitory regions.

3. Simulation Results

We carried out the simulations of the model in neural simulator *Nexus* in order to investigate whether our model in fact reproduced the characteristics of BO selective neurons. Stimuli used were squares, C-shaped figures, and overlapped two figures, which were similar to those used in physiological experiments [7]. We tested the model with a number of the variation in surrounding configuration, and obtained quantitative agreements with physiological data. As an example, we here show the response of three types of typical BO selective model-neurons (fig. 4). Black bars in the figure show the responses of the model neurons that are selective to BO and local contrast. Shown together is the neuronal responses re-plotted from [7](white bars). The responses of neuron *A* recorded from V2 show the preference to BO 'left' and contrast 'bright-dark'. Neuron *B*, also recorded in V2, shows the BO selectivity that is variant depending on the size of stimuli; the selectivity decreases as stimuli become larger. Neuron *C*, recorded from V4, shows a complex selectivity. This selectivity was realized by having two surrounding connections for each of two contrast directions.

The simulation results show that our model realizes the major characteristics of BO selective neurons observed in V2 and V4, including stimulus size variance and complex selectivities. These results

support our proposals that the surrounding contrast is crucial for BO determination, and that two spatial constraints on surrounding suppression/facilitation, which are stated in the previous section, are fundamental to the major characteristics of BO-selective neurons. Our preliminary research on population study also shows that these proposals are crucial to the realization of BO selectivity.

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Figure Captions

fig.1 A schematic illustration of the model. For the sake of simplicity, only a part of the model, the generation of BO 'right', is shown here. In the first stage, contrast is detected by the Gabor filters with preferred orientations denoted by 0, 90, 180, 270. In the second stage, surrounding contrast is integrated to determine the difference in the amount of contrast between those detected by G_0 and G_{180} within the inhibitory region and those detected by G_{90} and G_{270} within the excitatory region. Excitatory connection E_i extends to the right, and inhibitory connection I_j extends to the left. The third stage realizes two types of selectivity: co-selectivity to contrast 'bright-dark' along horizontal orientation and BO 'right', and co-selectivity to 'dark-bright' and 'right'. The selectivity to 'right' regardless of contrast is realized in the fourth stage.

fig. 2 The mechanism to determine BO selectivity is based on an asymmetrical arrangement of excitatory/inhibitory connections. A BO-left selective neuron has excitatory connections to the left of its CRF and inhibitory connections to the right (*a*). If a figure falls on to the left (*b*), the response of the left-selective neuron will be facilitated. If a figure falls on to the right (*d*), it will be suppressed. A solid line in *c* and a solid square in *b* and *d* indicate an input stimulus.

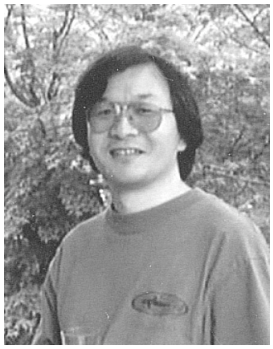
fig. 3 Contrast-independent BO selectivity is completed by taking the summation of the responses of a pair of contrast-dependant BO selective neurons (*a*). The neuron selective to contrast 'bright-dark' and BO 'left' responds to a white square on the left (*b*). The neuron selective to 'dark-bright' and 'left'

responds to a black square on the left (*c*). By taking the summation of the responses of the two neurons in the previous stage, the 'left' selective neuron responds to the both stimuli.

fig. 4 The simulation results. Black bars show the responses of the model neurons and white bars show the responses of the BO selective neurons re-plotted from [7]. The model is capable of reproducing a variety of selectivity reported in physiological experiments; BO 'left' and contrast 'bright-dark' selectivity (neuron *A*), size-dependency of BO selectivity (neuron *B*), and a rather complex BO selectivity (neuron *C*).

Authors

Haruka Nishimura took her BS and MS in Information Science at the University of Tsukuba, Japan, and is continuing the study toward a Ph.D. at the Graduate School of Systems and Information Engineering.



Ko Sakai received his BEng and MEng from the University of Electro-communications, Tokyo, and a Ph.D. in Bioengineering from the University of Pennsylvania, Philadelphia, PA. He is currently an associate professor at the University of Tsukuba, working on modeling visual perception.

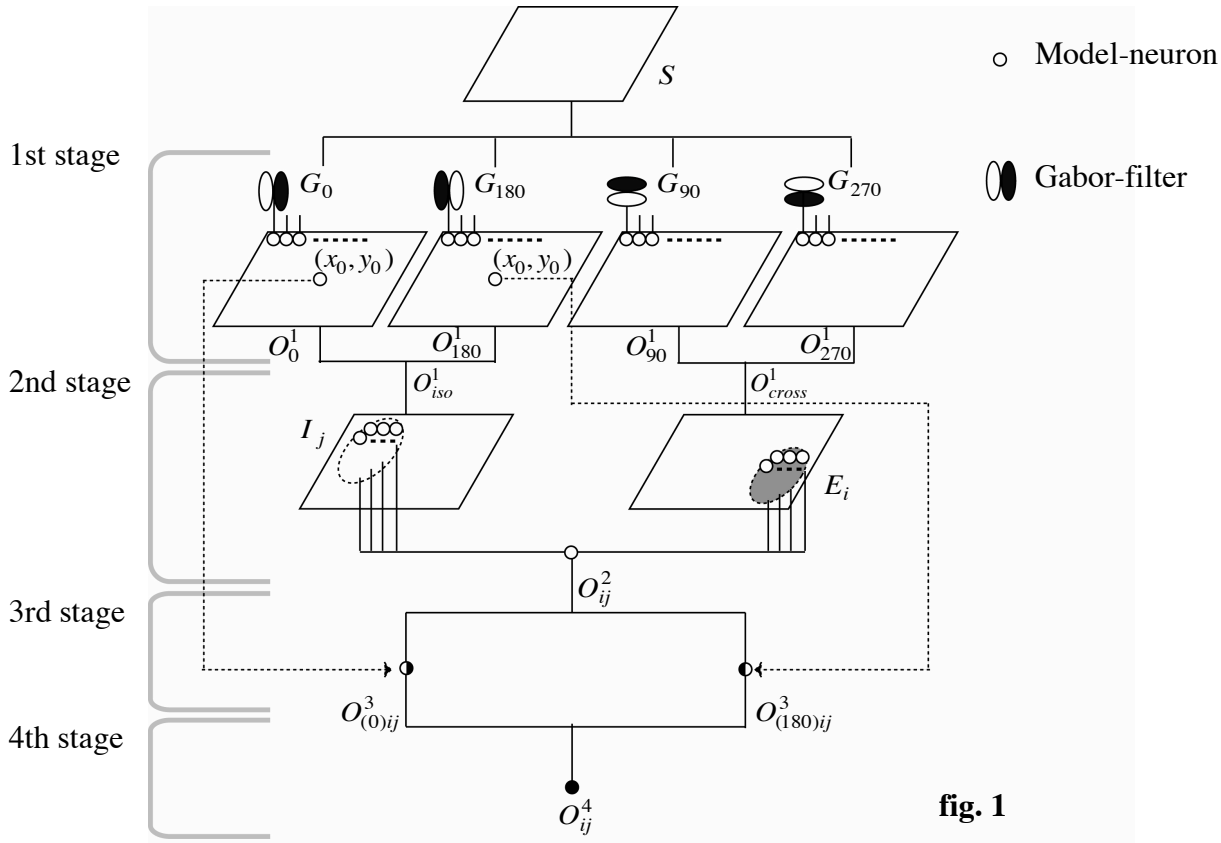
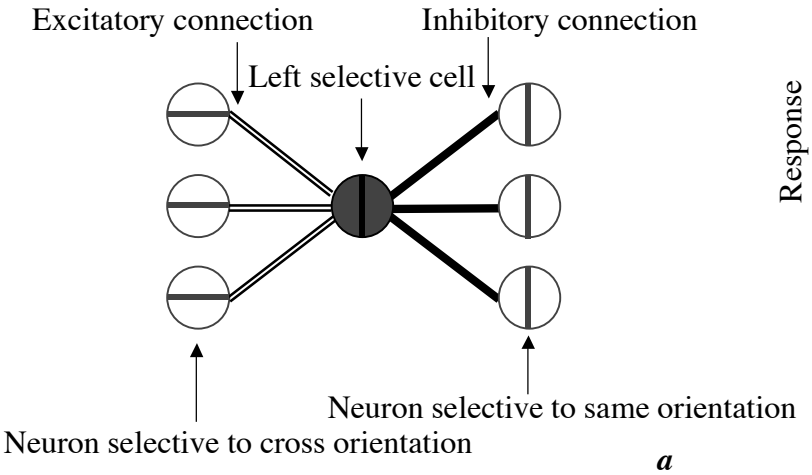
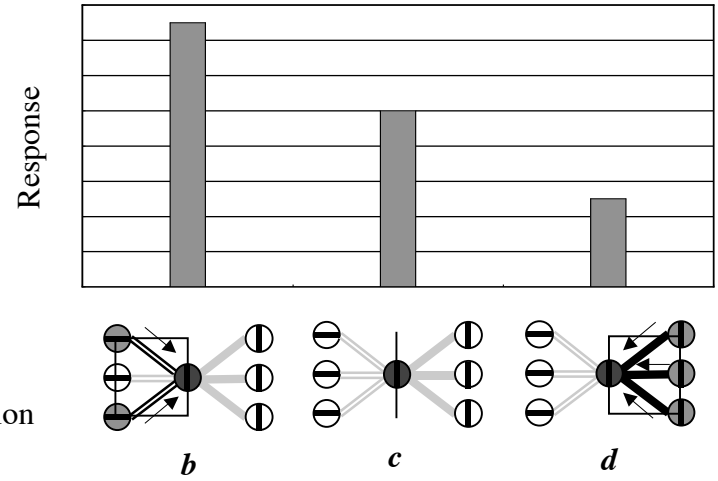


fig. 1

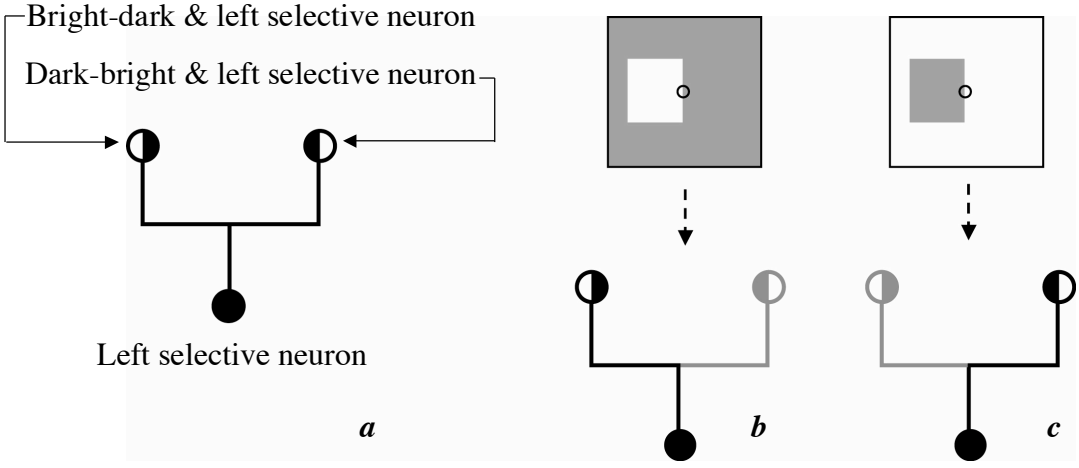


a



b *c* *d*

fig. 2



a *b* *c*

fig. 3

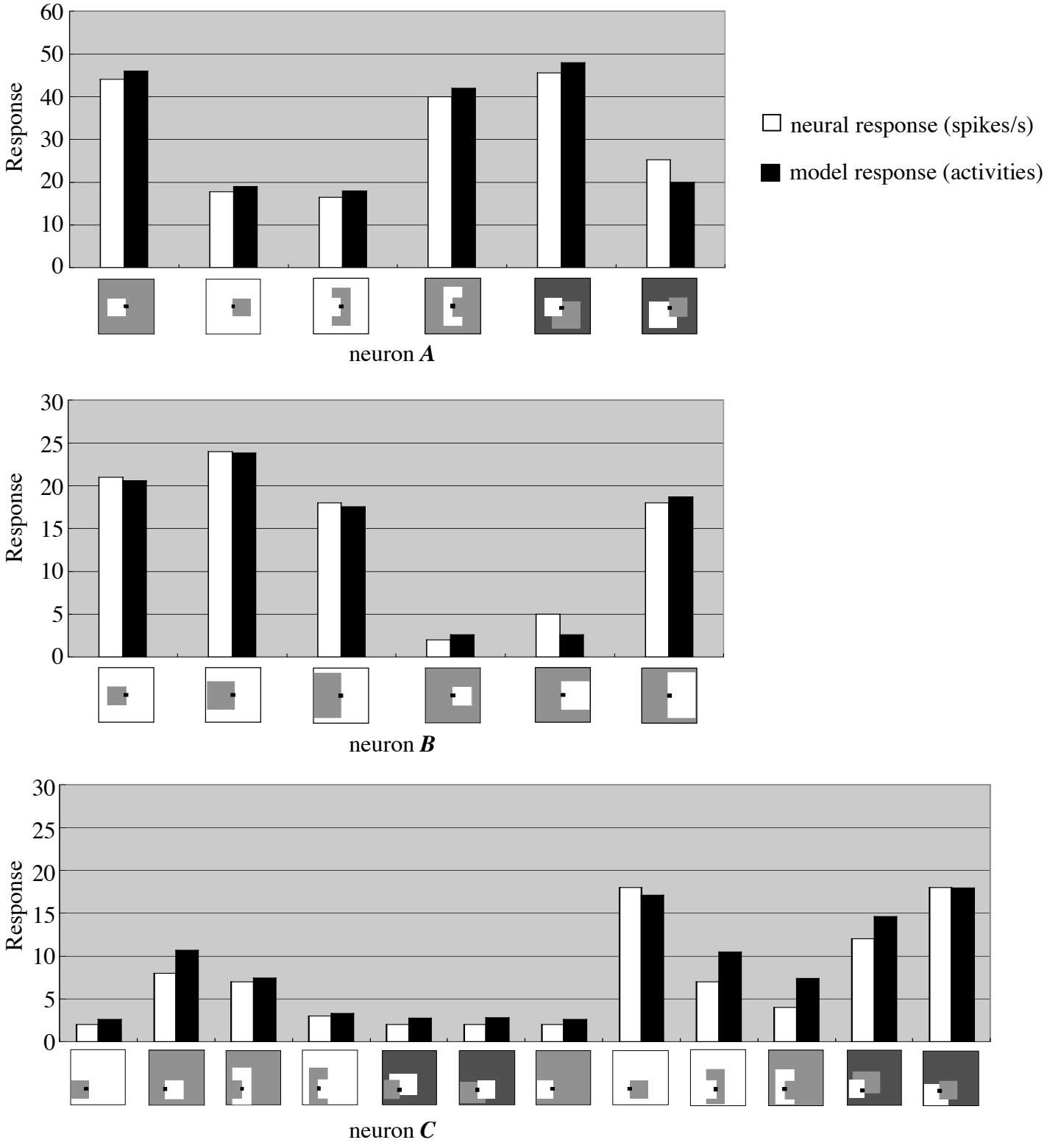

60
50
40
30
20
10
0
Response
neural response (spikes/s)
model response (activities)
neuron A
30
25
20
15
10
5
0
Response
neuron B
30
25
20
15
10
5
0
Response
neuron C

fig. 4