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

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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 paper, 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, suppression, facilitation, surrounding connection

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[9]. 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)[5][6]. 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[5], and (2) the surrounding suppression/facilitation reported in V1[2] plays a crucial role to integrate surrounding contrast information. Physiological and psychophysical studies [e.g. 1] have shown that the contextual modulation, which is represented in surrounding suppression/facilitation profiles, changes dramatically depending on the magnitude of contrast. Latest physiological experiments [3][4] have further revealed that the modulation depends also on both retinotopic-position and the orientation of surrounding stimuli, both relative to the CRF. Under low-contrast conditions, 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. 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.

2. The model

Our network model consists of four major stages, (1) detection of contrast by V1 simple-cell-like model-neurons[7], (2) integration of surrounding contrast by the mechanism of surrounding suppression/facilitation, (3) contrast dependent BO determination, and (4) contrast *in*-dependent BO determination. The model neurons in the first stage utilize even-symmetric Gabor filters with a variety in orientation; 0 deg. (*bright-dark* along the horizontal orientation, G_0 in Fig. 1), 90 deg. (G_{90}), 180 deg. (G_{180}), and 270 deg. (G_{270})[8]. The model neurons in the second stage realize the surrounding suppression/facilitation apparent in V1. Since we modeled a low-contrast condition in the previous report[10], we here present the model for a high-contrast condition in order to show that the BO could be determined in all cases by the identical principle. We represent the suppression by inhibitory connections

among the model neurons with the same preferred orientations (C_0, C_{180}) in the first stage, and facilitation by excitatory connections among the model neurons with preference to cross-orientations (C_{90}, C_{270}). The excitatory region extends to the direction that corresponds to BO preference of the model neuron, and the inhibitory region extends to the other direction to the excitatory region. The difference of the contrast information between that within the excitatory region and that within the inhibitory region is capable of reproducing BO selectivity. The response of the model neuron in the second stage is given by

$$R^2 = E * C_{90\_270} \square I * C_{0\_180} \quad .$$

E is the strength of the connection from the excitatory region, and I is that from the inhibitory region. We consider that this asymmetry in the spatial arrangement of the two connections plays a crucial role to realize BO selectivity. In the third stage, the response of model neurons, which shows selectivity to both BO and contrast, is given by

$$R^3_{\deg} = C_{\deg} \square S, \text{ where } S = C_{\deg} + R^2 \quad \text{If } S > 0, \text{ otherwise } R^3_{\deg} = 0 \quad .$$

Index *deg* shows contrast polarity, 0 deg (*bright-dark*) or 180 deg (*dark-bright*). In the last stage, a contrast-*in*dependent BO-selective neuron is realized by the summation of the activities among a pair of model neurons with different contrast selectivity (e.g. R_0 and R_{180}). A variety of the selectivity to BO and contrast reported physiologically was reproduced by the

variations of surrounding connections, including the spatial arrangement of excitatory and inhibitory regions, and the strength of connections.

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[5]. We tested the model with a number of 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.2). 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 [5](white bars). The responses of neuron A recorded from V2 show the preference to BO 'left' and the local 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 computed responses show good quantitative agreement with the neuronal responses for all of three

types.

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 proposal that the surrounding contrast is crucial for BO determination, and that surrounding suppression/facilitation is fundamental for the major characteristics of BO selective neurons.

Reference

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Figure Captions

Fig.1 A schematic illustration of the model. In the first stage, contrast is detected by Gabor filters with four orientations. In the second stage, surrounding contrast is integrated as to determine the difference in the amount of contrast between that detected by G_0 and G_{180} within the inhibitory region and that detected by G_{90} and G_{270} within the excitatory region. *SC1* shows the surrounding connections for a model neuron selective to 'right'. The excitatory region extends to the right and the inhibitory region extends to the left. Our model includes a

variety of surrounding connections (SC2, SC3, SC4, etc.) as similar to physiologically reported two dimensional response profile[4]. The model neurons selective to both BO and contrast are realized in the third stage, and those selective only to BO are realized in the fourth stage.

Fig. 2 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 [5]. The model is capable of reproducing a variety of selectivity reported in physiological experiments; left (BO) and bright-dark (contrast) selectivity (neuron A), size-dependency of BO selectivity (neuron B), and 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.

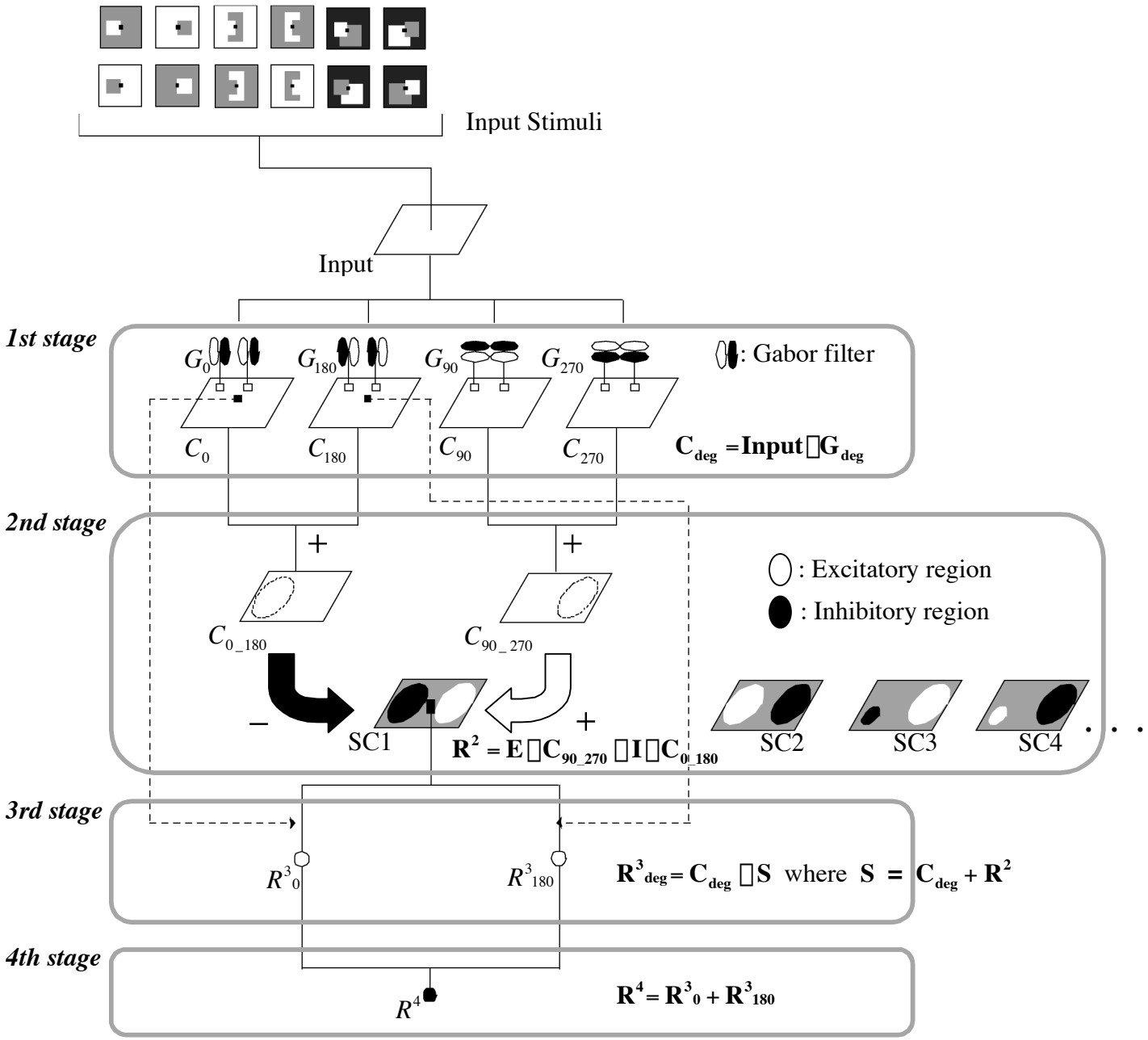
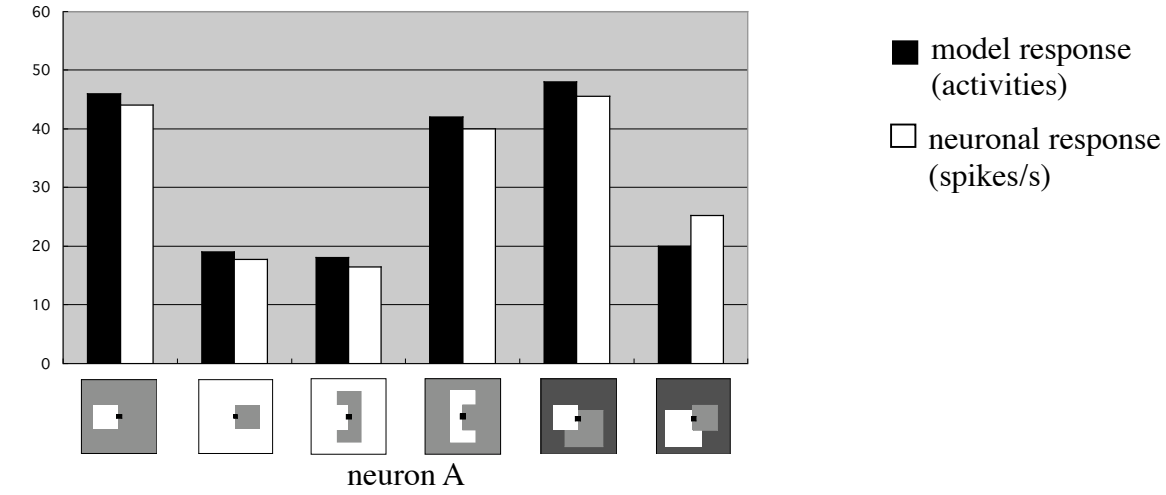
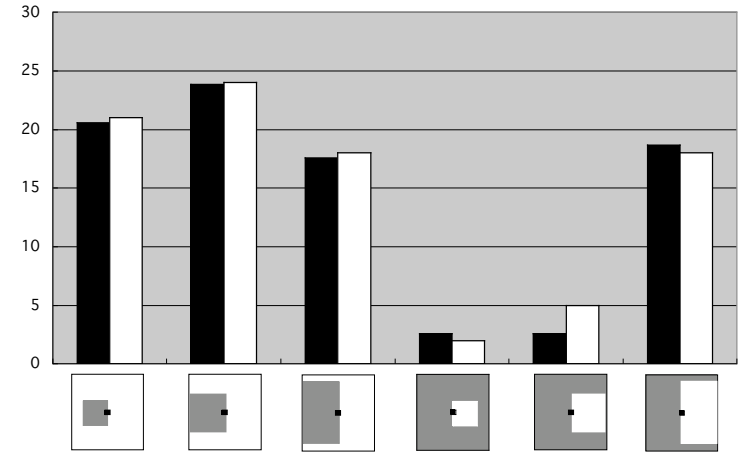

Input Stimuli
Input
1st stage
G_0 G_{180} G_{90} G_{270}
: Gabor filter
C_0 C_{180} C_{90} C_{270}
$\mathbf{C_{deg} = Input \otimes G_{deg}}$
2nd stage
: Excitatory region
: Inhibitory region
C_{0_180}
C_{90_270}
SC1
$\mathbf{R^2 = E \otimes C_{90\_270} \otimes I \otimes C_{0\_180}}$
SC2
SC3
SC4
3rd stage
R^3_0
R^3_{180}
$\mathbf{R^3_{deg} = C_{deg} \otimes S}$ where $\mathbf{S = C_{deg} + R^2}$
4th stage
R^4
$\mathbf{R^4 = R^3_0 + R^3_{180}}$

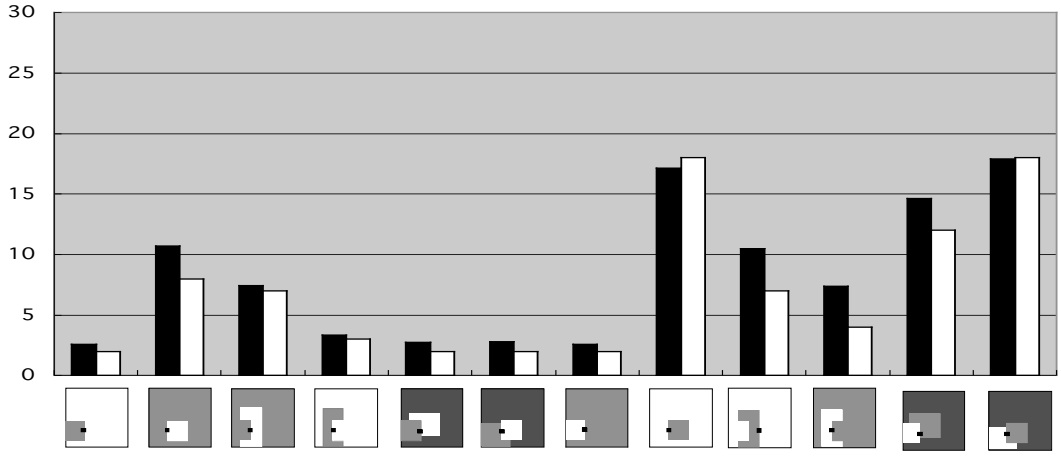
Fig. 1



neuron A



neuron B



neuron C

Fig. 2