Determination of Border-Ownership Based on the Surround Context of Contrast

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Abstract

We investigate the neural mechanisms for border-ownership (BO) determination, specifically whether the determination of BO is plausible from the contrast configuration within a certain range that extends beyond the classical receptive fields. The relevance of the contrast is suggested since the majority of BO-selective neurons in V2 and V4 show co-selectivity to the contrast. We hypothesize that the spatial structure of surrounding inhibition/excitation recently revealed in V1, or the similar structure in V2, is a key to integrate surrounding contrast to determine BO. The model reproduces a range of the neuronal activities responding to complex figures including occlusion.

Keywords: border-ownership, occlusion, contrast, surrounding inhibition/excitation, V2

1. Introduction

Discrimination of figure from ground is the essence for the perception of surface that is the fundamental source for the recognition of shape, spatial structure and objects. Recent physiological studies [8] have reported that neurons in monkey's V2 and V4 showed the selectivity to *border-ownership* (BO) that indicates the direction of figure (which side of the border owns the contour). About 80% of the BO-selective neurons were co-selective to the contrast polarity of a border. This strong contrast dependency led us to expect that local contrast surrounding the classical receptive fields (CRF) could be a basis for the determination of the direction of figure.

We propose a network model for the determination of BO based on the surrounding contrast configuration that is determined following the spatial structure of the surrounding connections revealed physiologically. Although a number of models that utilized T-junctions and ownership-junctions to determine BO have been proposed [e.g. 2], these models may not be physiologically realistic since neurons selective to such junctions have not been reported. It should also be noticed that the latency of BO-selective neurons is several to ten milliseconds [8], thus complex processes such as the detection of ownership-junction could not be involved. Our model determined BO solely from the surrounding contrast, and reproduced

quantitatively the responses of the BO-selective neurons in V2 and V4. The simulations showed that a variety and asymmetry of inhibitory and excitatory connections are crucial for the determination of BO selectivity.

2. The model

We propose a network model for the determination of BO based on two principles that are physiologically plausible; (1) BO is determined exclusively from contrast context surrounding CRF, and (2) a variety in surrounding connections produces a variety of BO selectivity reported by Zhou *et al*. Physiological studies [3, 7] have shown that surrounding inhibitory connections beyond CRF are mostly asymmetric around the CRF, and that the extent of the suppressive region is larger than the excitatory region in general. We propose that these surrounding connections play a key role in integrating surround contrast.

The model of contrast-dependent BO-selective neurons consists of three major stages; contrast detection by V1 simple-cell-like units [4], determination of surrounding contrast configuration, and contrast-dependent BO determination. The units in the first stage utilize even-symmetric Gabor filters with the variety in orientation; 0 deg. (*light-dark* along horizontal orientation, G_0 in Figure 1), 180 deg. (*dark-light*, G_{180}), 90 deg. (G_{90}), and 270 deg. (G_{270}) [5]. The second stage realizes the response of the neuron selective to both BO and edge

contrast. For the sake of simplicity, we consider here only horizontal orientations. Therefore, there are four kinds of selectivity in BO and edge contrast; '*left* and *light-dark*', '*left* and *dark-light*', '*right* and *light-dark*', and '*right* and *dark-light*'. The units in this stage detect the contrast configuration beyond CRF. The units have asymmetrical connections; excitatory connections extending to the preferred side of BO, and inhibitory connections extending to the opposite side. For instance, a unit selective to *left* (shown in Figure1) has an excitatory region extending to the left of the CRF and an inhibitory region extending to the right. This unit takes positive signals through the excitatory connections (E) among the units selective to the same orientation (C_{0_180}), and negative signals through inhibitory connections (I) among all units regardless of the orientation (C_{all}). In the last stage, the response of the model cell selective to both BO and edge contrast is given by

$R_{\deg} = C_{\deg} \square S$ if $S > 0$, otherwise $R_{\deg} = 0$, where

$S = C_{\deg} + E \square C_{0\_180} \square I \square C_{all}$

Index *deg* shows contrast polarity, 0 deg (*light-dark*) or 180 deg (*dark-light*). If a figure is brighter than background and placed on the left of the CRF (A in Fig.1), this unit fires much stronger than the figure placed on the right of the CRF (B in Fig.1).

It has been reported physiologically that some neurons are selective to BO

independent of edge contrast. Taking the summation of the responses of the units selective to the same BO but different contrast polarity, the model reproduces contrast-independent BO-selective neurons (cell ***c*** in Fig.2). A variety of the selectivity to BO and contrast reported physiologically were reproduced by the variations of surround connections, including the spatial arrangement of excitatory and inhibitory regions, and the strength of connections. We show three examples of such variations in the following section.

3. Simulation Results

We carried out the simulations of the network model in order to investigate whether in fact the model reproduces the responses of BO-selective neurons in V2 and V4. The bar graphs in Figure 2 show three examples of the results that indicate the responses of the model neurons (black bars) together with the corresponding neuronal responses re-plotted from H. Zhou *et al*. (white bars). Cell ***a*** (Fig.2 A) shows the selectivity to *left* and *light-dark*. Cell ***b*** (Fig.2 B) responds strongly to stimuli with a figure on left, and responds less to stimuli with a figure on right. This difference in response is less distinguishable if the size of a figure is larger, thus figure direction is ambiguous. We designed the inhibitory connections of cell ***b*** slightly different from those of cell ***a*** in order to match precisely to the actual neural responses. However, it should be noted that a typical model, cell ***a***, also reproduces this tendency to

figure size with less quantitative agreement. The characteristics of the responses of cell ***c*** (Fig.2 C) are rather complex. This selectivity can be realized by having two surrounding connections for each of two contrast directions, as shown in the figure. These simulation results show that our model reproduces quantitatively a range of the BO-selective neural responses based on surrounding connections. It is noteworthy that a slight variation of surround connections realizes precisely a variety of neural responses reported physiologically.

4. Discussions

The simulation study showed that (1) the context of the contrast surrounding the CRF is capable of determining BO without T-junction or ownership-junction detectors, and (2) a variety in asymmetric surrounding connections reproduces a range of BO-selectivity. The present model has excitatory connections among the cells with the same preferred orientation, and inhibitory connections among all cells regardless of the preferred orientation. It has been suggested that the function of surrounding inhibition/excitation depends on stimulus contrast [6]. The current configuration of the model seems to be appropriate for low contrast stimuli. We have developed a preliminary model for high contrast stimuli, in which functional surrounding connections are changed such that excitatory connections are valid among cells with the orthogonal preferred orientations, and inhibitory connection among the same

preferred orientation. This model also reproduced the responses that agreed quantitatively with physiological experiments. We have briefly shown that the determination of BO is plausible from the contrast configuration within a certain range that extends beyond the CRF, which was made possible by the spatial structure of surrounding inhibition/excitation.

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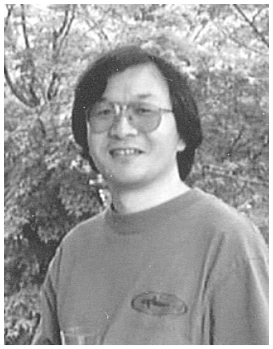

Ko Sakai received his BEng and MEng from the University of Electro-communications, Tokyo, and a Ph.D. in Bioengineering from the University of Pennsylvania, Philadelphia, PA. He is currently an associate professor at the University of Tsukuba, working on modeling visual perception.

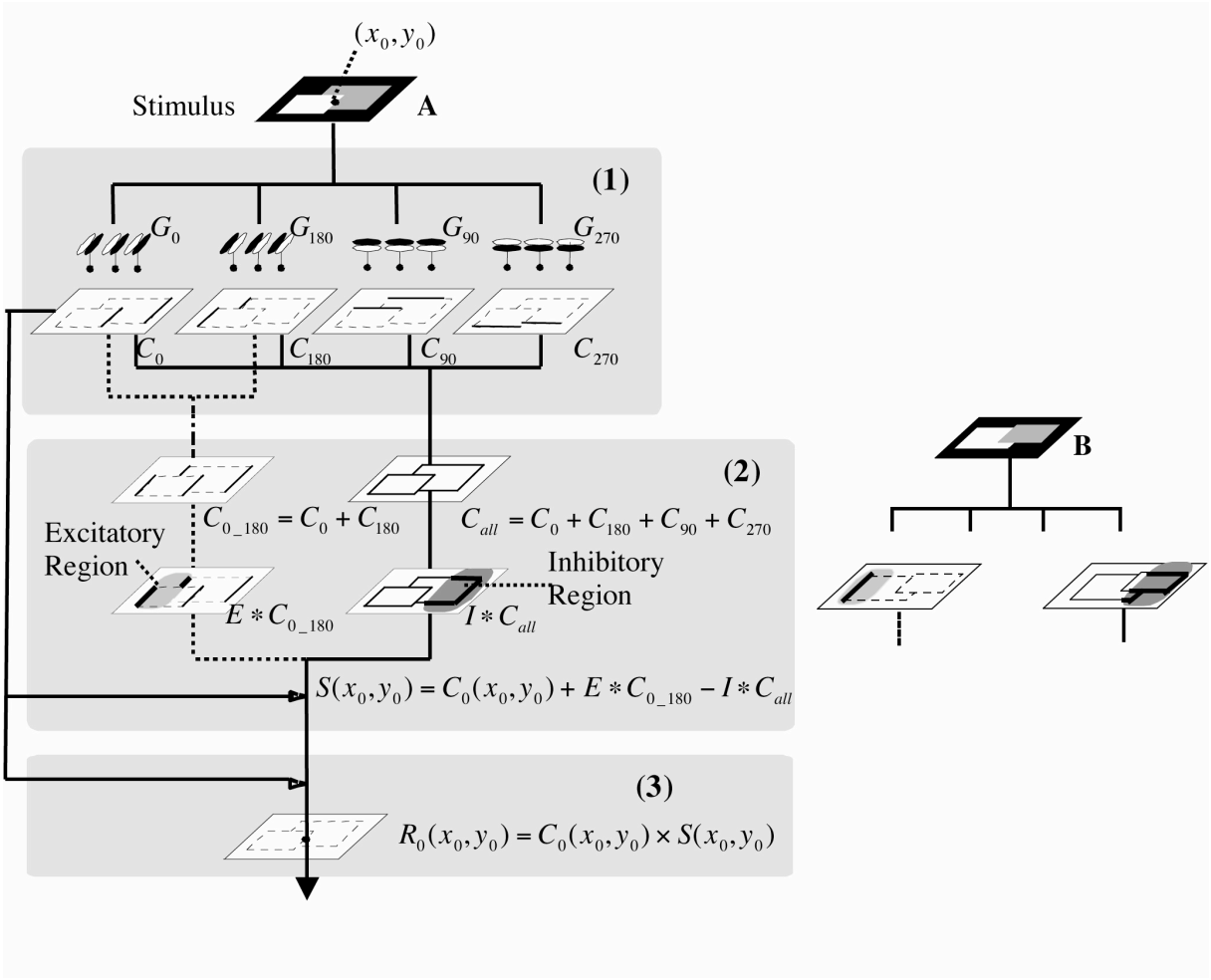

Figure1 An illustration of the model architecture. Shown here is a part of the model that realizes the response of a neuron selective to *left* and *light-dark*. The first stage (1) detects contours in four orientations. The activated regions for a given stimulus are drawn as thick solid lines. The second stage (2) determines contrast context. In this case, the amount of contrast within the excitatory region is larger than that in the inhibitory region, which leads to the activation of this *left* unit. In the last stage (3), the response of the previous stage is multiplied with C_0 so that the unit realizes the contrast dependent BO.

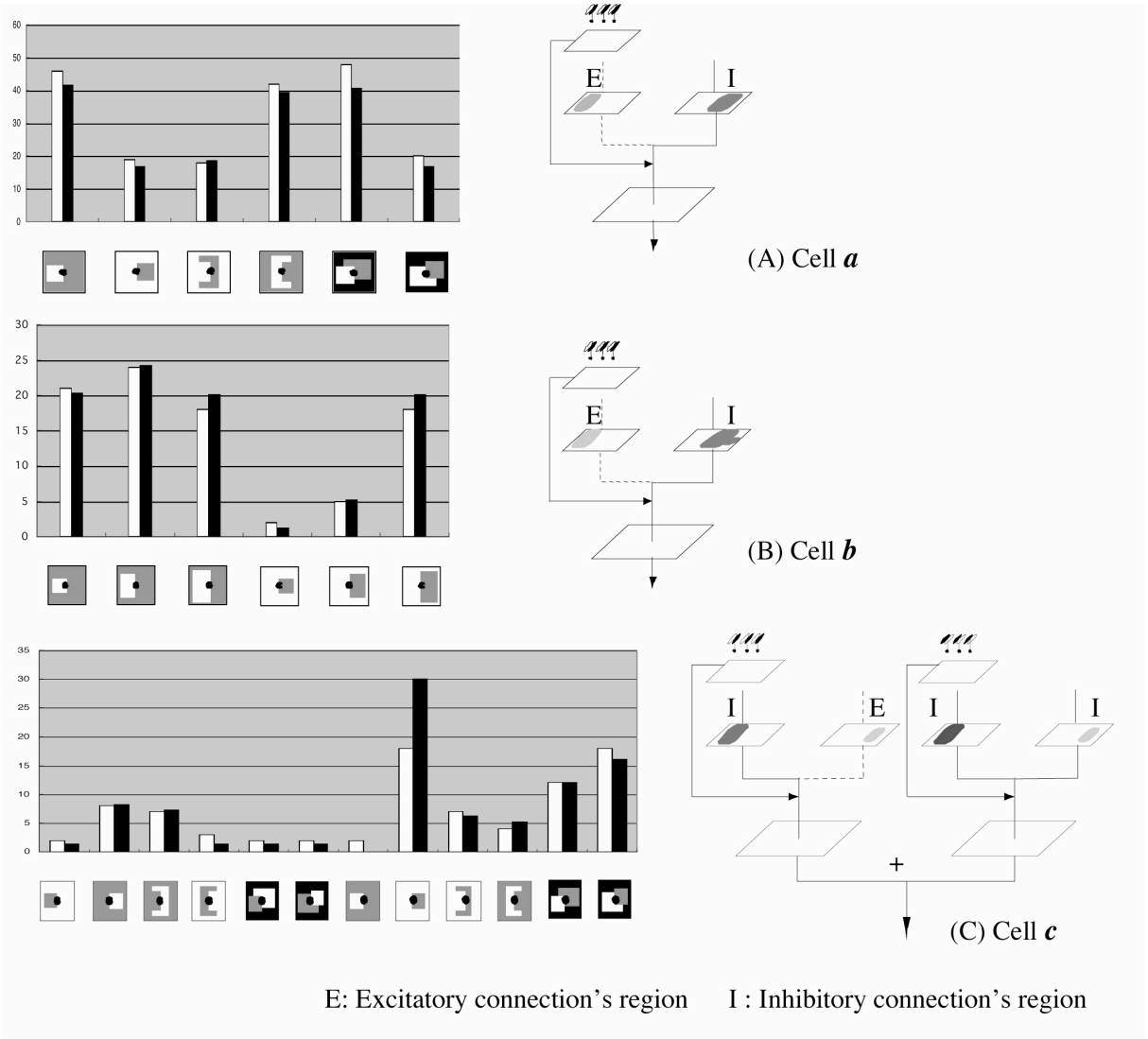

Figure2 The simulation results together with physiological data. Simply varying surrounding connections as similar to the structure of actual neurons (shown on the right of graph), the model is capable of reproducing a variety of selectivity and characteristics reported in physiological experiments; *left* and *light-dark* selectivity (A), size-dependency (B), and rather complex selectivity (C).