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

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ABSTRACT

We investigate 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 strongly since the majority of BO-selective neurons in V2 and V4 show co-selectivity to the contrast. The model includes colinear excitatory connections and longer, asymmetric inhibitory connections, and the colinear facilitation of the signals representing the direction of figure. The model reproduces a range of the neuronal activities responding to complex figures including occlusion.

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 have reported that neurons in monkey's V2 and V4 show activities corresponding to the direction of figure [1, 2, 3]. Zhou *et al.* [1] have distinguished types of neurons that showed selectivity to border ownership and/or contrast, about 80% of which were sensitive to contrast polarity. The selectivity to border-ownership and contrast was observed in stimuli with single squares, C-shaped figures and two overlapping squares.

However, underlying neural mechanisms for the figure determination have not been clarified. We propose a network model for determining figure/ground based on the context of contrast extending beyond the classical receptive field. Although a number of models that utilized T-junctions and ownership-junctions have been proposed [e.g. 4], a neuron selective to such junctions has not been reported physiologically. The strong contrast dependency apparent in the figure selective neurons in V2 and V4 led us to expect that local contrast surrounding the classical receptive field could be a basis for the determination of the direction of figure. We carried out the simulations of the network model in order to examine whether in fact the model reproduces the responses of V2 and V4 neurons reported physiologically [1]. The stimuli for the simulations included C-shaped figures and overlapping two squares. The results of the simulations show that the model is capable of determining figure/ground solely from the combinations of local contrast that can be gathered through asymmetric inhibitory connections and colinear connections apparent in the early vision.

2. Model

We propose a network model for figure/ground determination based on the context of stimulus contrast. The model consists of three major stages. The model first extracts local contrast and its orientation from stimuli by detecting intensity changes with V1-simple-cell-like units. The next stage realizes the selectivity to border ownership that is specific to contrast polarity. This function is originated from the combination of an elongated excitatory region and an asymmetric inhibitory region. The third stage shows the border ownership regardless of contrast polarity. Colinear facilitation plays an important role in this stage. The following sections describe major functions of each stage, and Figure 1 illustrates the diagram of the model.

2.1. Detection of Edge Contrast

The units in this stage realize the selectivity to edge contrast by taking the convolution with

Gabor filters. We utilized even-symmetric spatial-phases for each orientation and spatial location. For detecting “light-dark” edges, we use $G_1(x,y)$ that is responsive if intensity decreases from left to right along horizontal orientation (0 deg. phase). For detecting “dark-light” edges, we use $G_2(x,y)$ that is anti-phase (180 deg.) of $G_1(x,y)$.

2.2. Selectivity to Border Ownership with Specific Contrast Polarity

The second stage realizes the selectivity to edge contrast and border ownership. There are four kinds of selectivity; ‘light-dark & left’, ‘light-dark & right’, ‘dark-light & left’, and ‘dark-light & right’. For instance, if a figure is brighter than background, and placed on the left of the receptive filed, a ‘light-dark & left’ unit fires strongly. The units in this stage detect contrast configuration on and around the classical receptive field (CRF). The unit has an excitatory region elongated in the preferred orientation of the unit, and an asymmetrical and larger inhibitory region that extends to either side of the CRF, lateral to the preferred orientation. It has been reported for V1 neurons that excitatory regions beyond the CRF are elongated in the preferred orientation, which might be responsible for the colinear facilitation [5]. Other physiological studies have shown that inhibitory connections beyond the CRF are asymmetric around the CRF, and the extent of the suppressive region is larger than the excitatory region in general [6, 7]. These studies reported various shapes of the suppressive regions, which might be the origin of the variety of cellular selectivity in figure/ground determination. The model assumes the similar excitatory and inhibitory connections.

A physiological study showed that the neuronal response is less if the size of a stimulus square is larger thus the determination of figure direction is more ambiguous, while the response is maintained if an occluded square is larger [1]. This characteristic can be realized from the combination of a smaller excitatory region and a larger inhibitory region. The asymmetry of the inhibitory region is essential for the contrast selectivity. This asymmetry is also consistent with the neuronal behaviour that the response is smaller if a figure is larger so that the detection of figure/ground is difficult.

2.3. Selectivity to Border Ownership Invariant to Contrast Polarity

This stage realizes the selectivity to border ownership regardless of contrast polarity. The units in this stage integrate signals from the units in the previous stage with the same ownership but different contrast polarity at the same retinotopic position. If a stimulus consists of a single figure without overlap or occlusion, this stage makes correct judgement of the ownership. However, this is not the case for some stimulus configurations if stimuli are overlapped. When overlapping squares are presented, the units in this stage are incapable of determining correct ownership at the occluding contour because the contrast configuration itself could be equal in both the right and left sides of the contour.

We investigate whether colinear connections play a crucial role in the determination of figure direction, specifically in case of overlapping objects. Although it has not been clarified whether V2 neurons have the colinear connections similar to those in V1, we suppose such connections in V2 are plausible. Specifically, we consider that, given the colinear connections, we can exclude T-junction or ownership-junction detectors. We examined whether the ownership of the occluding contour is determined correctly if the colinear connections propagate the signals representing the figure direction from the extension of the contour that goes beyond the occluded figure where no overlap exists and the ownership is determined without ambiguity. Since the appropriate ownership of the contour on the extension is propagated to the occluding part, the correct ownership of the occluding contour is expected to be determined. Zhou, *et al.* [1] have reported that neurons in V2 and V4 signal correctly the figure direction in overlapping squares. Moreover, those signals are weaker if the length of the overlap is longer and the non-overlapping contour is shorter, which agrees with the prediction of our model. The collinear connection has been suggested to play a key role in the perception of contour and orientation in the primary visual cortex [8, 9], together with nonlinear properties of the receptive fields [10].

3. Simulation Results

We carried out the simulations of the network model to investigate whether the model reproduces a variety of neuronal characteristics reported in physiological experiments. The model showed the correct determination of figure directions in a variety of stimuli. An example of the results is shown in Figure 2, which indicates the correct determination of figure directions for a single square, C-shaped objects, and two overlapping squares. We next examined whether the model reproduces the properties of V2 and V4 neurons selective to border ownership. For example, we have confirmed that the model neurons show less activity if an overlapping part is larger in a stimulus. The model also reproduces the neuronal characteristic that the distinction between figure and ground is less if the size of a figure is larger, as shown in Figure 3. The model reproduces a variety of major properties of the V2 and V4 figure-selective neurons reported physiologically. The results indicate that the model is capable of determining figure/ground solely from the combinations of local contrast information gathered from outside the classical receptive field.

4. Conclusions and Discussions

The present study has shown that the context of contrast is capable of determining figure direction without T-junction or ownership-junction detectors. The major components of the model include the asymmetric connections of V1 neurons that gather the contrast information from outside the classical receptive fields, and the collinear connections in model V2 that propagates signals corresponding to figure direction. Zhou *et al*. have reported that neurons in V2 and V4 selective to figure direction responded correctly to a figure even if only a partial view of a single square was presented so that the other side of the square was invisible [1]. They have also reported that the neurons responded correctly to figure if a stimulus had an elliptic shape. Our preliminary results show that the model reproduces quantitatively the reported neural responses for a partial view of an object including those with an arbitrary shape.

5. References

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Figure Captions

Figure 1 The architecture of the model that determines figure/ground, which consists of three major stages: contrast detection, computation of contrast dependent border-ownership, and determination of border-ownership invariant to contrast polarity.

Figure 2 The responses of the model neuron selective to the direction of figure (*left*) and local contrast (*light-dark*). Shown together is the neuronal responses replotted from Zhou, *et al*. [1]. The model shows good quantitative agreement with the cellular responses for stimuli including a C-shaped object and two overlapping squares.

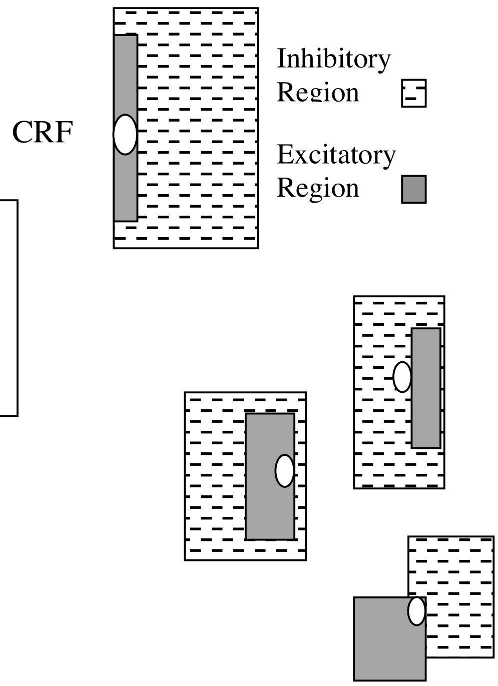
Figure 3 The activities of the model unit are less distinguishable if the size of a figure is larger. The corresponding neuronal responses are reported from Zhou, *et al*. [1]. The simulation results show good quantitative agreement with the physiologically measured activities.

< 1st stage >

Detection of Edge Contrast

< 2nd stage >

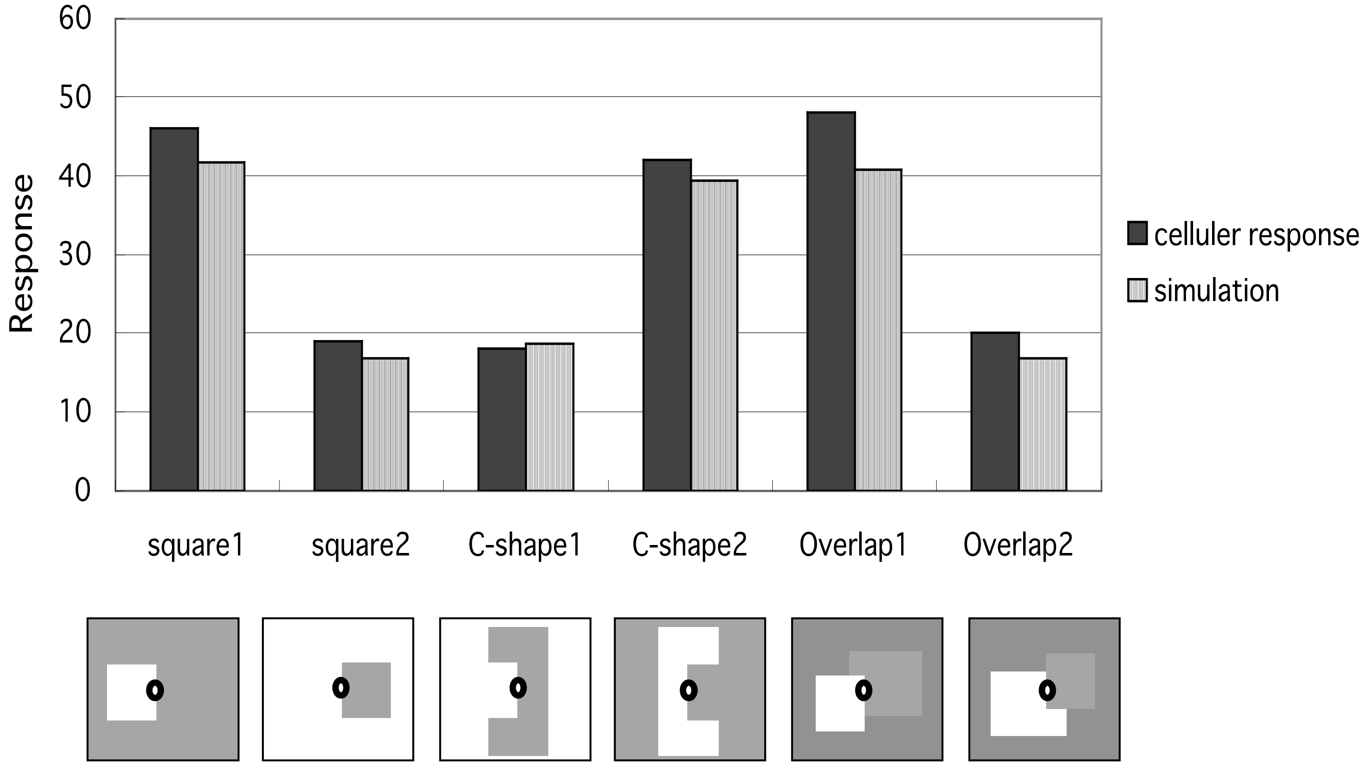
Realizing selectivity to
Border Ownership with
Specific Contrast polarity



< 3rd stage >

Realizing selectivity to
Border Ownership Invariant to Contrast polarity

Fig.1


60
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Response
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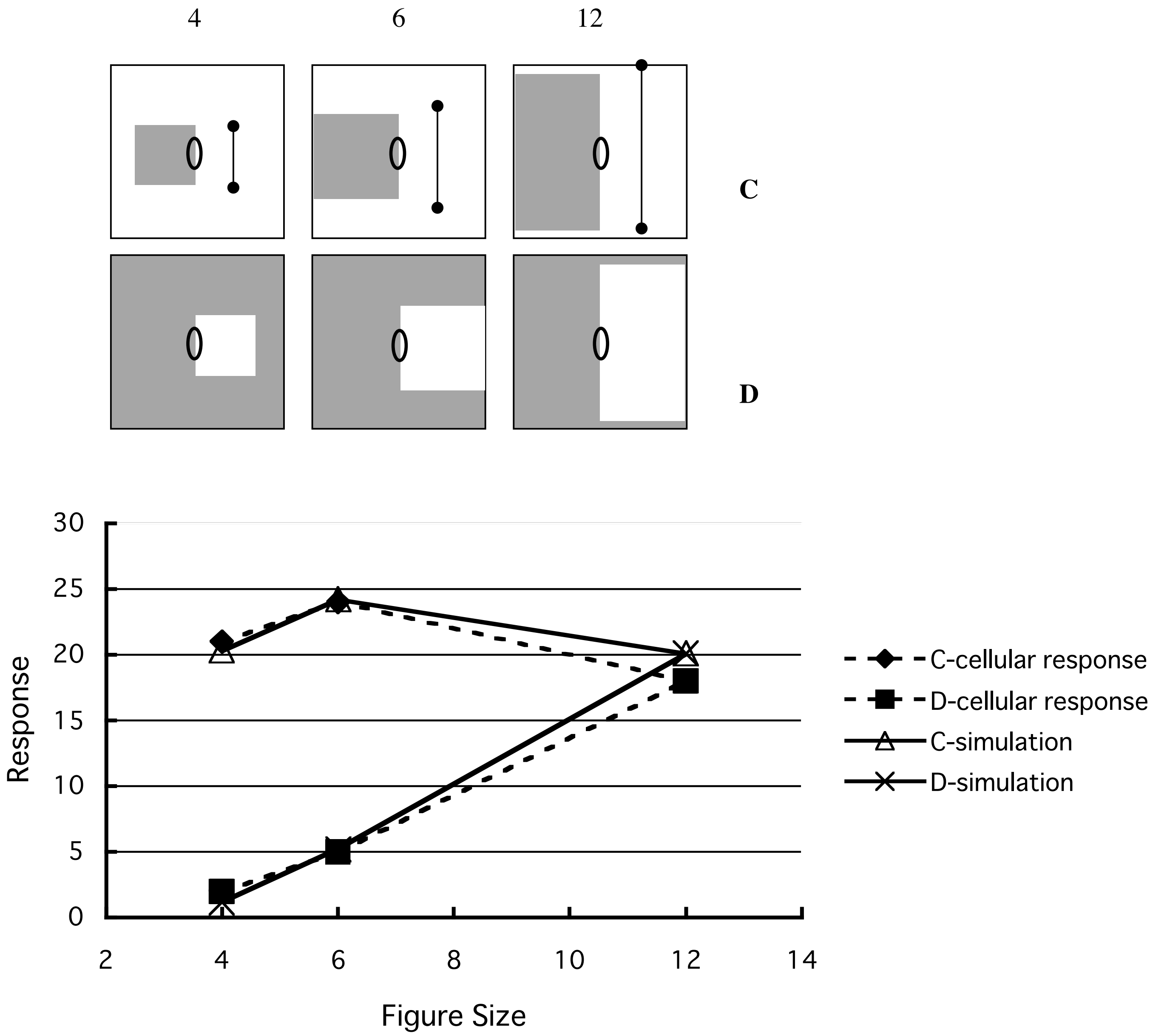
square1
square2
C-shape1
C-shape2
Overlap1
Overlap2

Fig.2



4
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Response
Figure Size
C-cellular response
D-cellular response
C-simulation
D-simulation

Fig.3