Early Recurrence Enables Figure Border Ownership

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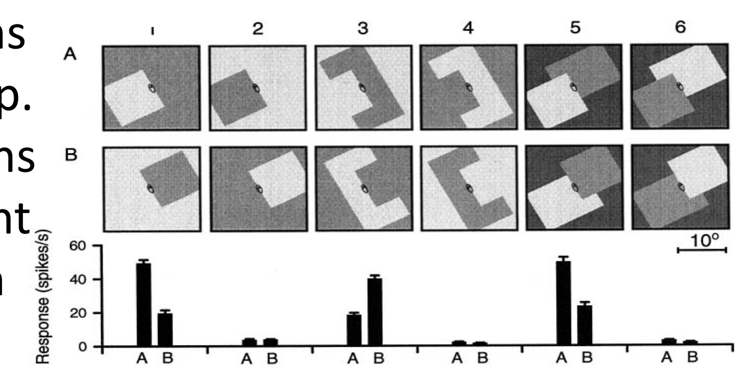
1. Introduction

The face-vase illusion introduced by Rubin demonstrates how one can switch between two different interpretations depending on how the figure outlines are assigned [1]. This border ownership assignment is an important step in the perception of forms.

Rubin's face-vase illusion (adapted from [1]).

Zhou et al. [2] suggested that certain neurons in the visual cortex encode border ownership. They showed that responses of these neurons not only depend on the local features present in their classical receptive fields, but also on the contextual information.



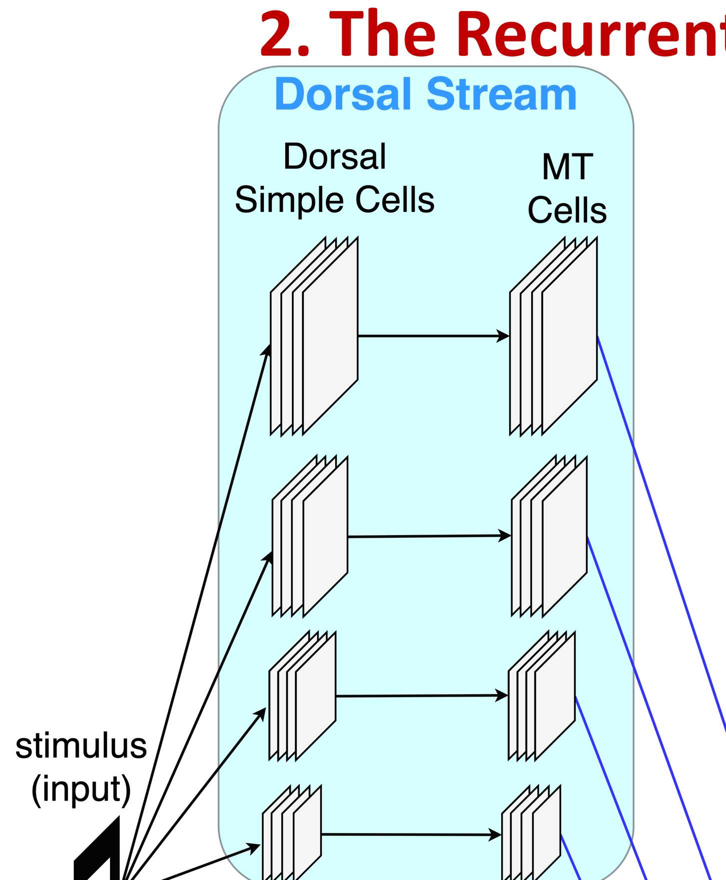
Example of a V2 cell tested with single squares, c-shaped stimuli, and overlapping figures (adapted from [2]).

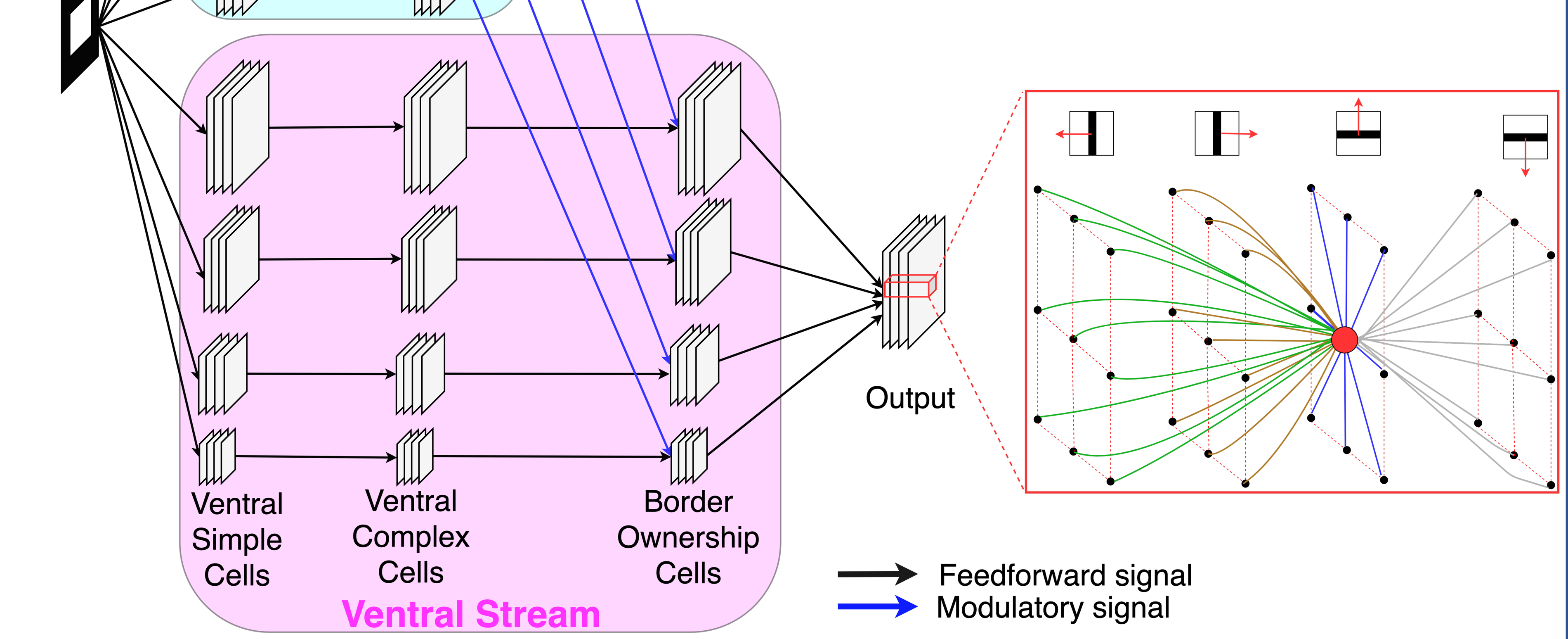
Suggesting a mechanism for border ownership assignment in the brain:

- Models based on feedback from higher ventral areas or lateral connections have been proposed [3-8]
- The plausibility of models exclusively based on lateral connections was ruled out [6, 9, 10]
- Further evidence [11] suggests that ventral feedback even from V4 is not fast enough to provide context to BO neurons in V1 and V2 with latencies about 70 ms.
- As a result, the border ownership assignment mechanism in the brain is still a mystery to be solved.

2. The Recurrent Border Ownership (RBO) Model

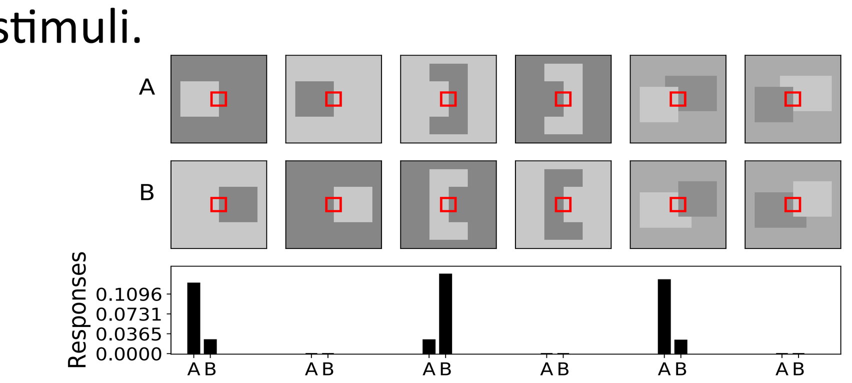
- We propose the Recurrent Border Ownership (**RBO**) model based on early recurrence from the dorsal pathway as well as lateral modulations within the ventral stream.
- Dorsal modulations from MT in our model provide the global context due to their relatively large receptive fields. Also, MT neurons are computationally fast (~ 39 ms latencies [12]).
- Lateral connections in our model are implemented using relaxation labeling (RL). A few iterations of relaxation labeling provides local context to the border ownership neurons.



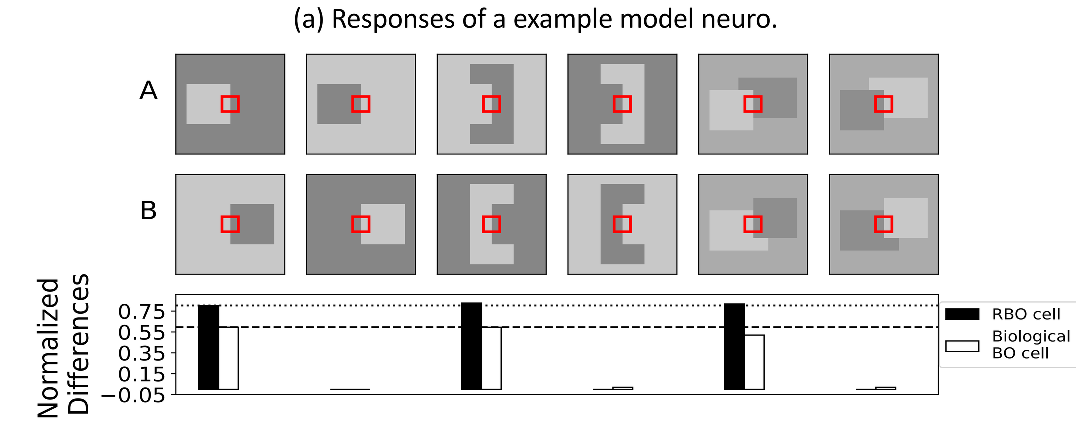


3. Simulation Results

Example of a model border ownership responses in (a). The difference of responses to stimuli with figure on either side of the border is observed. Figure (b) depicts the normalized difference of responses for the model neuron in (a) and the biological BO cell shown earlier. Similar to the biological neuron, our BO cell consistently maintains the difference of responses across all stimuli.

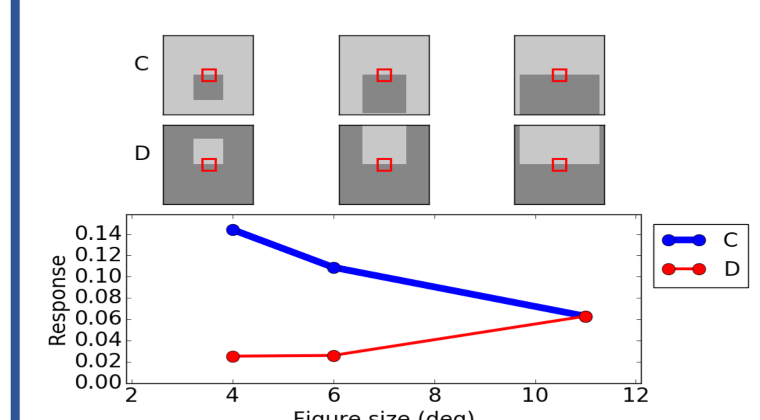


(a) Responses of a example model neuro.

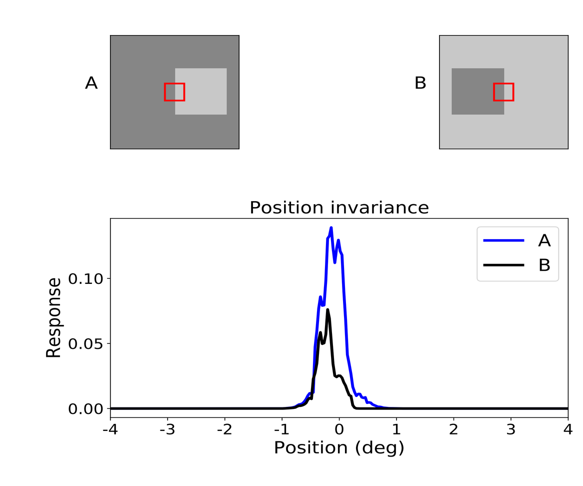


(b) Comparison of normalized difference of responses between model and biological BO cells, where normalized differences are computed as:

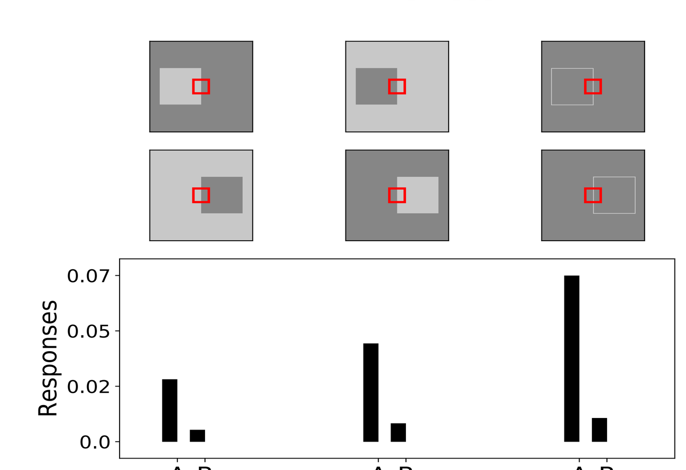
$$\text{Normalized Differences} = \frac{R_{\text{preferred}} - R_{\text{non-preferred}}}{\max(R_{\text{preferred}}, R_{\text{non-preferred}})}$$



(a) Invariance to size of figure in model border ownership cells. The difference in responses are observed up to an indistinguishable figure-ground stimulus.



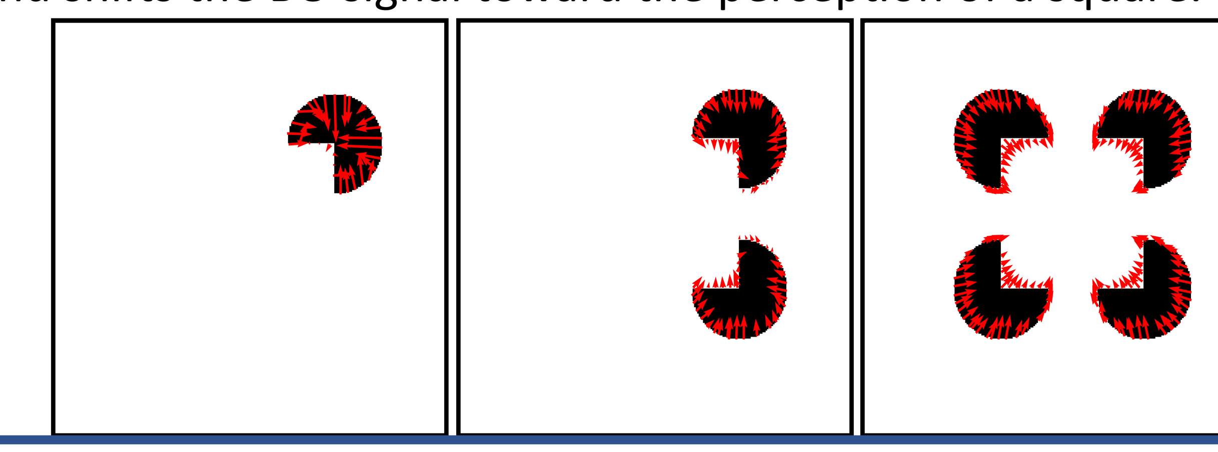
(b) Invariance to position. Our model border ownership neurons, similar to the biological border ownership cells, maintain the difference of responses with changes in the position of the border within their receptive field.



(c) The RBO neurons exhibit invariance to solid/outlined figures.

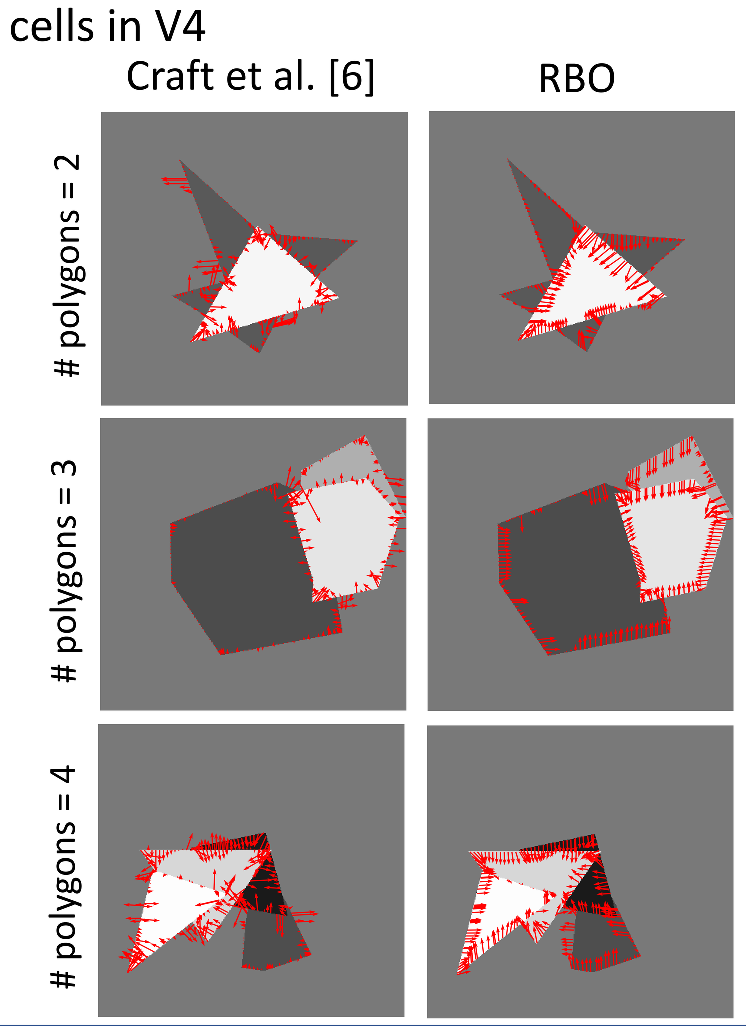
3. Simulation Results (Cont.)

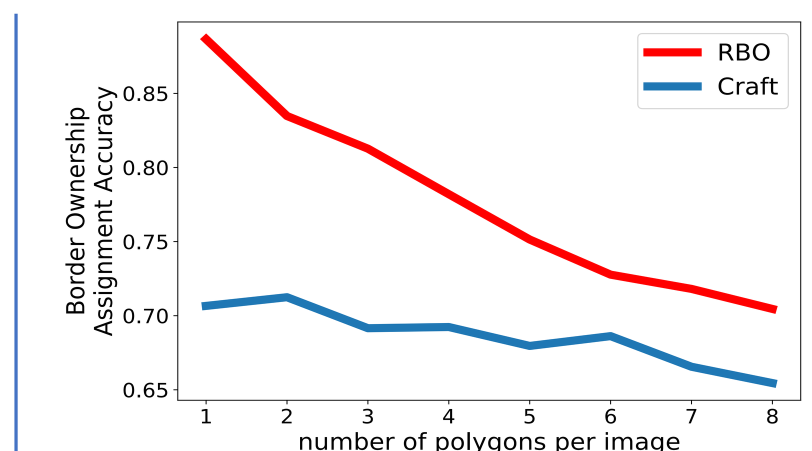
Can the RBO model explain the Kanizsa's square? Our RBO cells with dorsal modulations signal the illusory bar and square in the middle and right examples as occluding figures due to two features of our model: first, our model MT cells with large receptive fields are activated along the edges of the illusory square, not much affected by the absence of a portion of the edge. Second, the large surround afforded by dorsal modulations provides contextual information to BO cells and shifts the BO signal toward the perception of a square.



4. Randomly Overlapping Polygons Dataset (ROPD)

- In order to quantitatively compare the performance of our model with that of existing computational models for border ownership assignment, we created a dataset of randomly overlapping polygons with the number of polygons varying between 1 and 8, with a total of 800 images
- We compared our model border ownership assignments with that of Craft et al. [6], a benchmark model for border ownership assignments based on feedback from grouping cells in V4





Our model outperforms that of Craft et al. [6] in border ownership assignment. Both models have a drop in performance with an increase in scene complexity due to more competing features on either side of the border. A similar performance decline with increase in scene complexity was observed in human subjects in an ultra-rapid categorization task [13].

5. Conclusion

- We introduced RBO for border ownership assignment based on dorsal and lateral modulations.
- The time course of border ownership neurons and MT cells support our hypothesis that the dorsal stream provides contextual information to border ownership neurons in the ventral stream.
- The RBO model combines global and local context and unlike previously introduced models does not depend on priors such as convexity, T-junctions, etc.
- The RBO model outperforms Craft's model on a dataset of randomly overlapping polygons.
- Our model border ownership neurons show side-of-figure preferences similar to those of biological cells.

References

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Acknowledgements

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