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Abstract

The Boundary Contour System neural vision model reproduces perceptual illusory boundary formation by a conjunctive boundary completion process within a large cellular receptive field. The conjunctive chain allows the same kind of conjunction to occur across multiple receptive fields, which allows for sharper, more flexible boundary completion.

The Boundary Contour System (BCS) together with the Feature Contour System (FCS) neural vision models by Grossberg & Mingolla [1] account for a wide range of psychophysical phenomena including visual illusions such as the Kanizsa figures, illustrated in Figure 1. The model suggests that visual perception involves two distinct but interacting mechanisms, a boundary system which represents image edges and the interactions between them, and a feature system which mediates surface and brightness perception between boundaries represented in the BCS system. Figure 2 illustrates the basic architecture of this model. The cells at (A) represent a layer of light sensitive cells. The cells at (B) represent cortical simple cells that receive input from the light sensitive cells through oriented receptive fields, so that different cells at (B) respond to edges of different orientations at (A). The cells in layer (C) receive input from pairs of cells in layer (B) which represent edges that are parallel in orientation but of opposite direction of contrast. The three big blocks at each layer represent three horizontally adjacent locations in the visual field.

A principal feature of the BCS model is its ability to perform boundary completion between oriented edges that are approximately aligned, like the inducers of the Kanizsa figures which produce illusory boundaries. The mechanism responsible for this boundary completion is a layer of cooperative cells depicted in layer (D) of the figure, which receive input from layer (C) through
large, double lobed oriented receptive fields shaped somewhat like bow-ties. Like the receptive fields of layer (B), the bow-ties occur at every orientation at each spatial location, but unlike those fields the cooperative cell receptive field spans many adjacent spatial locations (only two are shown in the figure) in a direction parallel to the orientation of the inputs preferred by the cooperative cell. For example, the horizontal cooperative cell depicted in the figure has a receptive field that is horizontally aligned to receive input from layer (C) horizontal cells at horizontally adjacent locations. Grossberg and Mingolla observe that the boundary completion process occurs only inwards between inducers, never outward beyond inducers. This feature is implemented in the model by a conjunctive constraint between the two lobes of the filter, which specifies that the cooperative cell will not fire unless it receives input from both lobes simultaneously.

The design of the receptive field of the cooperative cell in the BCS model must strike a balance between two competing factors. On the one hand, the receptive field must be small in order to accurately trace along a fine boundary without loss of information due to spatial averaging. On the other hand the receptive field must be as large as the largest gap which must be spanned by such boundary completion. As can be seen in the Kanisza triangle in Figure 1, this gap can be considerably larger than the resolution of the finest boundaries in the image. The solution proposed in the BCS model is to encode complex orientational properties into the structure of the cooperative receptive field, so that only those cooperative cells which are located along an optimal line of completion between two inducers would receive significant input. This is achieved by way of complex geometries that define the optimal orientation of an input to the filter, as a function of
location from the filter center. For example, inputs that are along the central axis of the filter have an optimal orientation parallel to that central axis, as depicted in Figure 2 (C), whereas inputs that are slightly off axis would be optimally aligned at an angle to the axis, as indicated by the dotted inputs in Figure 2 (C), because that would be the orientation of a smooth curve passing through those points from the center of the filter. The actual function used in the BCS is rather complex, and is an area of ongoing research. At best, this kind of scheme can only be an approximation, because there are more degrees of freedom in the number of possible smooth curves between two points than can be represented in the filter.

In the absence of the conjunctive constraint, the cooperative cells could be made with much smaller receptive fields, and yet they could perform smooth boundary completion over large angular separations by a parallel relaxation scheme whereby each cell responds both to the oriented input signal and to the orientations represented in neighboring cooperative cells. In regions between oriented inputs therefore the cooperative cells would relax into a field of smooth curves, connecting the two inputs, as suggested in Figure 3. This relaxation is somewhat analogous to the behavior of iron filings in a magnetic field; individual filings line up into chains, and the chains propagate and channel the magnetic field into regions where it would otherwise be much weaker.

The absence of the conjunctive constraint however causes this system to form illusory boundaries outwards into featurless space as well as inwards between inducers, which is contradictory to observed illusory boundaries that are only seen to form inwards between inducers. If a conjunctive behavior could be implemented as a global emergent property of local interactions however, then the system would have the desirable properties for curved boundary completion as well as the conjunctive property required to match the psychophysical findings.
Figure 5 illustrates a conjunctive chain made up of Boolean AND gates, such that each AND gate in the chain receives its inputs from its two adjacent neighbors, while the two gates at the ends of the chain receive Boolean inputs $I_1$ and $I_2$. Even when both Boolean inputs are TRUE, the body of the chain will always remain inactive because of the strict conjunctive constraint at each link of the chain. If the gates were replaced by Boolean OR gates, then any activation at either end of the chain would always activate the whole chain, after which the chain would always remain active regardless of the state of the inputs. The emergent global behavior of this system therefore would be runaway positive feedback leading to saturation, which blocks the system from responding any further to the pattern of inputs. Lehar [2] suggests a solution to this problem by means of a softer conjunctive constraint, by replacing the Boolean AND operation with its analog equivalent, i.e. multiplication, and by establishing one additional constraint, that in the absence of input, the minimum value of each node is some small positive value. Further application of nonlinearity to the system in the form of the Grossberg shunting equation for each node produces a system that exhibits a global conjunctive property by way of local interactions.

Figure 7 shows the results of application of the conjunctive chain in a full image simulation [2]; (A) shows the input image, composed of three vertical lines. (B) shows the beginnings of boundary completion, after 60 iterations, and (C) shows the complete chain at equilibrium in a full dynamic simulation. Note how the resultant illusory boundary forms a smooth natural curve between the inducers, bending mostly near the middle of the curve. Note also that no completion occurs outward from the isolated line ending.

References
