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Abstract

An extension to the Boundary Contour System model is proposed to account for boundary completion through vertices with arbitrary numbers of orientations, in a manner consistent with psychophysical observations, by way of harmonic resonance in a neural architecture.

The Ehrenstein figure shown in Figure 1 (A) is one example of many possible combinations of visual features that give rise to a perception of illusory boundaries. Such illusory phenomena provide clues to the mechanisms of early vision, and have been modeled with neural network models such as the Boundary Contour System (BCS) and Feature Contour System (FCS) by Grossberg & Mingolla [1]. A principle feature of the BCS model that accounts for illusory boundary formation is the bipolar cooperative cell, depicted in Figure 2(A), postulated to exist at all orientations and all spatial locations in the visual cortex, whose pair of large elongated receptive fields detect pairs of boundaries that are both parallel and spatially aligned, and perform illusory boundary completion between them. In the case of the Ehrenstein figures, the inducing boundaries themselves are illusory, in the form of orthogonal “end cuts” at the ends of the radial lines.

The minimal Ehrenstein figure shown in Figure 1 (B) also forms an illusory figure, although the exact shape of that figure has been described by subjects variously as a square (C), a circle (D), or a diamond (E). This figure suggests that the mechanism of illusory boundary formation is capable of performing such completion around sharp vertices, like the corners of the square or the diamond. Since the bipolar cooperative cell of the BCS is hard-wired specifically for colinear boundary completion, this raises the question of how this mechanism can be generalized for angular boundary completion through such vertices. Grossberg [2] suggests a variety of specialized cooperative cells for every combination of orientations, like the example for vertical right angles.
Variations on the cooperative cell- conventional BCS (A), specialized right angle cell (B), and generalized rosette of cells (C).

Figure 2.

shown in Figure 2 (B). The problem with this solution is a combinatorial explosion of the number of possible edges at possible relative orientations, each of which would be reproduced at all orientations and all spatial locations, which would require an inordinate amount of specialized neural hardware. Heiko Neumann [3] proposes a more generalized solution consisting of a “rosette” of cells of all orientations, each of which has just a single oriented receptive field, as depicted in (C). Neumann proposes that cooperative competitive feedback interactions among the cells in the central ring could be designed to allow exactly two and only two orientations to be active at any time. This model would allow for boundary completion between any pair of orientations through a vertex. It would still require separate rosettes for vertices composed of three, four, or more intersecting oriented edges, each with appropriately tuned cooperative competitive dynamics.

Figure 3.

Acoustical harmonics in (A) a linear tube, (B) a circular tube, and (C) orientational cells.

Lehar [4] proposes a still more general solution whereby only a single rosette of hardware is required to encode arbitrary numbers of orientations at any vertex, by way of harmonic patterns of standing waves stimulated in the central ring of cells. Harmonic resonance is a natural property of
many systems in nature, such as vibrating elastic solids, resonant acoustic cavities, electrical circuits, lasers, and even chemical reaction diffusion systems, and has the property of generating periodic spatial patterns. The mechanism of these harmonic systems can be extremely simple, governed only by simple interactions between local elements, and yet they are capable of producing a wide array of spatial patterns. Unlike models using receptive fields, the scale of the interaction between vibrating elements, often just local molecular forces, is much smaller than the size of the emergent waveforms. A principal property of harmonic systems is a tendency to form regular periodic patterns that are integer multiples of some fundamental. For example, the harmonic frequencies of a resonant acoustic cavity are integer multiples of the fundamental wavelength, which is determined by the length of the cavity, as shown in Figure 3 (A). Although a harmonic system like an acoustic cavity can respond to any waveform of any wavelength, it has a special behavior in the presence of any of its harmonics, i.e. it resonates to, and amplifies the components of a signal that are compatible with its own harmonics. In the case of a closed space, such as a circular tube, the harmonics subdivide the interval from 0 to $2\pi$ into integer multiples of the full circle, as shown in (B). While the spatial pattern of nodes is fixed in a linear tube by the boundary conditions at the ends of the tube, in the circular tube a harmonic pattern can occur at any orientation.

A harmonic resonance of this sort can be postulated as a property of neural dynamics in a ring of neural tissue, creating periodic patterns of activation and inactivation within that ring. The interactions between adjacent neurons in the ring need not be in the form of spiking transmission or chemical synapses, but might consist of gap junctions, producing a direct electrotonic coupling with a transmission speed that is considerably faster than synaptic transmission. A ring of neurons coupled in this manner would constitute a single unified syncytium analogous to a single rigid body that moves as a unit in response to applied forces. The tiny residual propagation delay between neurons in the tissue would be analogous to the elastic flex between atoms in the rigid body, which is the property that accounts for harmonic oscillations. Application of excitatory input to some points in the ring, and inhibitory input to other points would set up a harmonic pattern of activation that would subdivide the ring into an integer number of alternately excited and quiescent regions. In an oriented representation such a periodic pattern would represent orientational periodicity, as shown in (C), which would tend to perform boundary completion through one or more of these periodic patterns.

Computer simulations of such orientational harmonics make specific predictions about the illusory boundaries resulting from a wide range of visual input features. For example, the model predicts that a vertex formed by the termination of a single orientation would tend to form illusory boundaries in directions indicated in Figure 4 (A), and a vertex formed at a right angle would tend to form illusory boundaries as depicted in (B). The orientational harmonic responsible for each potential completion is indicated by the numbers in the figure. For example at the line ending in (A), the second harmonic finds a strong input at six o’clock, which primes it for completion in the twelve o’clock direction, whereas the third harmonic responds to that same input by projecting two “rays” of potential completion at two and ten o’clock. These potential completions will remain subliminal or inactive unless they find evidence in the form of compatibly aligned orientations. If for instance an additional vertical edge were presented at twelve o’clock in (A), the second harmonic would find strong evidence in both of its two favored directions, which would generate a perceptible illusory boundary in that direction, as predicted in Figure 5 (A), with an
Figure 4.

Model predictions of potential illusory boundary formation for line ending and right angle. The fourth harmonic would also benefit from such an input, although this would represent only 50% of its favored pattern, causing an increase in the intensity of its potential grouping signals at three and nine o'clocks. The presence of oriented features in those directions would stimulate perceptible illusory boundaries there too, as shown in (E) and (F). Third harmonic grouping is illustrated in (C) and (D), and similar groupings are shown for the right angle.

Figure 5.

Various grouping predictions of the harmonics of the line ending and right angle.

References


