Appendix: Equations and Parameters

This section describes BCS and FCS equations that incorporate the enhancements and revisions discussed in the text. The equations are similar to those in Gove *et al.* (1995) and Grossberg and McLoughlin (1997), but they eliminate processes that are not rate-limiting in the targeted data: Only a single scale is used, and hypercomplex and bipole cells in the BCS and monocular filling-in domains (FIDOs) in the FCS are not included. All equations were solved at equilibrium, except for the binocular filling-in equation which was solved using fourth-order Runge-Kutta with time step 0.0000025. Most of the equations were solved at equilibrium to fit the targeted data. However, as Arrington (1994) and Francis and Grossberg (1996a, 1996b) illustrate, these equations can also be solved in real-time to fit dynamically evolving data.

A1 ON Channel

FACADE cell activities obey the classical membrane equation (Hodgkin 1964; Grossberg 1973, 1983):

$$C_m \frac{dV(t)}{dt} = -[V(t) - E_{excit}]\, g_{excit}(t) - [V(t) - E_{inhib}]\, g_{inhib}(t) - [V(t) - E_{leak}]\, g_{leak}, \qquad \text{(A1)}$$

where the parameters E represent reversal potentials, g_{leak} is a constant leakage conductance, and the time varying conductances $g_{excit}(t)$ and $g_{inhib}(t)$ represent the total excitatory and inhibitory inputs to the cell. The $V(t)$ terms that multiply these conductances in (A1) represent shunting interactions.

For computational simplicity, the present simulations use only an ON channel. The ON channel activity x_i at each cell i is described by an on-center off-surround network whose cells obey membrane equations:

$$\frac{dx_i}{dt} = -\alpha_1 x_i + (U_1 - x_i)\, C_i - (x_i + L_i)\, S_1. \qquad \text{(A2)}$$

Taken together, the shunting and on-center off-surround interaction in (A2) yield ratio processing and normalization by cell activities x_i (Grossberg, 1973, 1983); *i.e.*, contrast normalization. In (A2) the decay rate $\alpha_1 = 100$; the excitatory and inhibitory saturation levels are $U_1 = 50$ and $L_1 = 50$ respectively; and the center C_1 and surround S_1 terms are defined by Gaussian kernels:

$$C_1 = \sum_p C_p I_{i+p}, \tag{A3}$$

and

$$S_1 = \sum_p S_p I_{i+p}, \tag{A4}$$

with

$$C_p = \frac{A_1}{2\pi {\sigma_c}^2} \exp\left(-\frac{p^2}{{\sigma_c}^2}\right), \tag{A5}$$

$$S_p = \frac{A_2}{2\pi {\sigma_s}^2} \exp\left(-\frac{p^2}{{\sigma_s}^2}\right), \tag{A6}$$

and $A_1 = 1.1, A_2 = 15.987, \sigma_c = 0.1, \sigma_s = 1.5$. At equilibrium:

$$x_i = \frac{\sum_p (U_1 C_p - L_1 S_p) I_{i+p}}{\alpha_1 + \sum_p (C_p + S_p) I_{i+p}}, \tag{A7}$$

and the output signal $X_i = [x_i]^+$, where $[x]^+ = max(x, 0)$. The values of A_1 and A_2 were chosen so that a uniform pattern of I_i inputs causes an x_i response pattern whose amplitude is approximately one-tenth as large. This assures a positive response to ganzfelds.

A2 Simple Cells of the BCS

Even-symmetric and odd-symmetric simple cell receptive fields centered on location i were defined using even and odd Gabor kernels. For our 1-D brightness simulations, these terms are:

$$S_i^{odd} = \left[\sum_p {s_p}^{odd} X_{i-p}\right]^+ \tag{A8}$$

and

$$S_i^{even} = \left[\sum_p {s_p}^{even} X_{i-p}\right]^+, \tag{A9}$$

where

$${s_p}^{odd} = A \sin(2p) \exp\left[-\frac{1}{2}\left(\frac{p^2}{{\sigma_p}^2}\right)\right] \tag{A10}$$

and

$${s_p}^{even} = A \cos(2p) \exp\left[-\frac{1}{2}\left(\frac{p^2}{{\sigma_p}^2}\right)\right], \tag{A11}$$

$A = 1.0$, $\sigma_p = 1.0$, and $\sigma_q = 0.75$. The size of the kernel is defined to be $-4 \le p \le 4$ in (A8) and (A9).

A3 Complex Cells of the BCS

Complex cell activities c_i fuse together the left and right monocular simple cell boundaries. In this implementation, the two monocular images are at zero disparity:

$$\frac{dc_i}{dt} = -\alpha_3 c_i + (U_3 - c_i)\sum_p C_{i+p} S_{i+p} - (c_i + L_3)\sum_p E_{i+p} S_{i+p}, \tag{A12}$$

where $\alpha_3 = 0.1, U_3 = 1.0$, and $L_3 = 1.0$. The term S_{i+p} is the sum of even and odd simple cell activities:

$$S_i = S_i^{even} + S_i^{odd}. \tag{A13}$$

The Gaussian on-center and off-surround kernels are:

$$C_{i+p} = A_1 \exp\left[-\mu^c p^2\right] \tag{A14}$$

and

$$E_{i+p} = A_2 \exp\left[-\mu^s p^2\right], \tag{A15}$$

where $A_1 = 1.0, A_2 = 1.0$. $\mu_c = 1.5$ and $\mu_s = 0.06$. At equilibrium:

$$c_i = \frac{\sum_p \left(U_3 C_{i+p} - L_3 E_{i+p}\right) S_{i+p}}{\alpha_3 + \sum_p \left(C_{i+p,d} + E_{i+p,d}\right) S_{i+p}} \tag{A16}$$

The output from the complex cells is defined as $C_i = [c_i]^+$.

A4 Binocular Filling-In Domain of the FCS

The binocular filling-in domains (FIDOs) receive input from both the left and right eye monocular ON cells. The binocular activities y_i that fuse the left and right eye FCS signals are defined as in (6):

$$\frac{dy_i}{dt} = -\alpha y_i + (B - y_i)\sum_{k=1}^{n} C_{ki}\left[f\left(x_{kL}\right) + f\left(x_{kR}\right)\right] - (y_i + D)\sum_{k=1}^{n} E_{ki}\left[g\left(x_{kL}\right) + g\left(x_{kR}\right)\right], \tag{A17}$$

where C_{ki} and E_{ki} are Gaussian kernels and where the nonlinear signal functions $f(x)$ and $g(x)$ are defined as follows:

$$f(x) = \frac{[x - ,]^{+2}}{\alpha + [x - ,]^{+2}} \tag{A18}$$

and

$$g(x) = \frac{[x - ,]^{+}}{\alpha + [x - ,]^{+}}. \tag{A19}$$

The excitatory function thus grows less quickly than the inhibitory signal function. At equilibrium,

$$y_i = \frac{B\sum_{k=1}^{n} C_{ki}\left[f\left(x_{kL}\right) + f\left(x_{kR}\right)\right] - D\sum_{k=1}^{n} E_{ki}\left[g\left(x_{kL}\right) + g\left(x_{kR}\right)\right]}{\alpha + \sum_{k=1}^{n} C_{ki}\left[f\left(x_{kL}\right) + f\left(x_{kR}\right)\right] + \sum_{k=1}^{n} E_{ki}\left[g\left(x_{kL}\right) + g\left(x_{kR}\right)\right]}. \tag{A20}$$

The output signal is $Y_i = [y_i]^+$. The diffusive filling-in of surface activity Ω_i is defined by the following equations (Grossberg and Todorović, 1988):

$$\frac{d\Omega_i}{dt} = -M\Omega_i + \sum_{p\in N}\left(\Omega_p - \Omega_i\right)\Psi_{pi} + Y_i, \tag{A21}$$

where the decay rate $M = 0.1, B = 1.5, D = 1.0$, N_i is the set of nearest neighbors of cell i, and the permeability coefficient that controls the rate of diffusion is:

$$\Psi_{pi} = \frac{\delta}{\kappa + \epsilon\left(C_p + C_i\right)}, \tag{A22}$$

where $\delta = 50{,}000, \kappa = 1.0, \epsilon = 50{,}000$. In (A22), C_p and C_i represent boundary signals at positions p and i that are determined by the complex cell activities at these positions. Solving (A21) at equilibrium yields:

$$\Omega_i = \frac{\sum_{p\in N_i}\Omega_p\Psi_{pi}}{M + \sum_{p\in N_i}\Psi_{pi}}, \tag{A23}$$

A5 Computer Implementation

The computer implementation of the BCS/FCS model is written in C and runs on Sun Workstations. The following sections describe how the equations are used to arrive at the simulation graphs.

A5.1 Isobrightness curves

Because of the computational costs in solving equation (A21) using numerical integration for many points, the isobrightness curve in Figure 1c was generated by varying both left-eye and right-eye inputs and evaluating y_i using equation (A20) at the central binocular FCS cell in the array of 165 cells. The cell's receptive field is nine units wide and (x_{kL}, x_{kR}) were created using equation (A7). The network input I_i corresponds to a single point stimulus presented to both left and right input streams.

The MATLAB contour function was then used to plot the isobrightness curves of y_i values. These curves connect points corresponding to equal binocular FCS filling-in signals. All other things being equal, for a step increase in input luminance, as used in the Anstis and Ho (1998) experiments, larger luminance steps lead to larger filling-in signals which will correspond to larger filled-in values (Grossberg and Todorović, 1988) and so the lines in Figure 1c will connect points of equal filled-in surface brightness signals.

A5.2 U Shape curve

The same functions were used to generate the U shape curve seen in Figure 2b but the left eye input luminance was fixed at 1000 and the right-eye input luminance was varied from 0 to 1000.

A5.3 Ganzfeld Simulations

In the ganzfeld simulations, we needed only fit the 12 ganzfeld luminance data points of Bourassa and Rule (1994), so numerical integration of equation (A21) was now tractable. Ganzfeld inputs were created as follows for a 1-D array of 165 cells:

$$I_i = 2\sqrt[3]{\left(90^2 - (c-i)^2\right)} + 800, \tag{A24}$$

where $c = 83$ is the center node of the network and $i = 1, 2, \ldots, 165$. The term $90^2 - (c-i)^2$ generates a smooth 1-D cross section that falls off from the center. The cube root function allows the function fall-off to be less steep with a slightly convex shape. Although Bourassa and Rule (1994) do not discuss the fall-off in luminance at the periphery, typical experimental procedures allow at most a 5% difference between center and periphery (Knau and Spillmann, 1997). The addition of 800 in (A24) defines a base luminance. This luminance cross-section corresponds to the fixed left-eye ganzfeld input. Less luminous right-eye ganzfeld inputs can be created by multiplying each I_i by a scaling factor as dictated by the Bourassa and Rule (1994) luminance values. The final filled-in equilibrium value is scaled using equation (8) in Section 4.2 and plotted beside the average magnitude data from Bourassa and Rule (1994).

A5.4 Cogan data simulations

The Cogan inputs were created by using 1-D cross-sections of the left- and right-eye inputs in Figure 5. I_i was set to 0.0 for the black contours and black disk input regions, otherwise I_i was set to 0.6 for the before-flash condition. For inputs containing the flash, I_i was set to 1.0 for those regions that contained the flash, all other inputs are unchanged. Each flash stimulus was 45 cells wide, out of the total 165 cells. The width of the black contour surrounding a flashed stimulus was 4 cells. Model detection sensitivities were modeled by taking the final filled-in binocular FCS signal and applying equation (9) as per Section 4.3.