Towards a Theory of the Laminar Architecture of Cerebral Cortex: Computational Clues from the Visual System

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One of the most exciting and open research frontiers in neuroscience is that of seeking to understand the functional roles of the layers of cerebral cortex. New experimental techniques for probing the laminar circuitry of cortex have recently been developed, opening up novel opportunities for investigating how its six-layered architecture contributes to perception and cognition. The task of trying to interpret this complex structure can be facilitated by theoretical analyses of the types of computations that cortex is carrying out, and of how these might be implemented in specific cortical circuits. We have recently developed a detailed neural model of how the parvocellular stream of the visual cortex utilizes its feedforward, feedback and horizontal interactions for purposes of visual filtering, attention and perceptual grouping. This model, called LAMINART, shows how these perceptual processes relate to the mechanisms that ensure the stable development of cortical circuits in the infant, and to the continued stability of learning in the adult. The present article reviews this laminar theory of visual cortex, considers how it may be generalized towards a more comprehensive theory that encompasses other cortical areas and cognitive processes, and shows how its laminar framework generates a variety of testable predictions.

1. Introduction: The Need for a Theory of the Laminar Structure of Cortex

Although much has been discovered about the response properties of individual cortical neurons and about the structure of topographic maps, comparatively little is presently known about the functional roles of the layers of cerebral cortex. Two factors in particular make this a promising topic for future research: first, the six-layered structure of cortex is, with only minor exceptions, remarkably uniform across mammalian species and across cortical areas. This suggests that fundamental design principles may underlie its architecture. Second, new experimental techniques for probing the laminar circuitry of cortex have recently been developed, opening up new opportunities for addressing previously intractable problems.

However, the profuse inter- and intralaminar connections within cortex seem to form a bewildering and impenetrable tangle. Rich and reciprocal corticocortical projections further deepen the puzzle. Given the complexity of these connections, the prospects seem dim for attempts to start from the anatomy and to use that to derive function. In contrast, the converse route – examining the functional roles played by cortex and asking how these might be mapped onto its detailed laminar structure – is not so underdetermined. Indeed, it can be argued that only by starting from an analysis of the information processing known to be carried out by cortex can initial footholds be gained that help towards interpreting its intricate laminar circuitry.

The cortical area whose functional roles have been best delineated, and whose laminar anatomy and physiology have been most intensively studied, is primary visual cortex. We have recently developed a computational model of visual cortex that attempts to assign specific functional roles to the feedforward, feedback and horizontal connections of cortical areas V1 and V2. This article will review the main computational ideas that underlie this model, and will go on to consider the following more general questions:

- How can analysis of the functional roles of cortex help us to interpret its laminar circuitry?
- Might other cortical areas share architectural design principles in common with visual cortex?
- What might be the functional role of top-down corticocortical feedback?
- Can novel and testable predictions be derived from the model, with a view to motivating new experimental investigations of cortical laminar circuitry?

2. From Analysis of Function to Interpreting Laminar Circuitry: The Preattentive–Attentive Interface Problem

Cortex has the ability to integrate information from a remarkably diverse range of sources: bottom-up signals stemming from peripheral sense organs, top-down feedback carrying goal-related information from higher cortical areas, and intrinsic horizontal signals carrying contextual information from neighboring regions within the same cortical area.

These three distinct types of signal not only coexist within a single cortical area, but also interact and mutually shape each other's processing. For example, Roelfsema and colleagues have produced evidence that top-down attention in macaque V1 propagates horizontally along the neural representation of a traced curve, that attention will spread between curve segments that smoothly connect to each other, but not between curve segments that fail to satisfy this property of Gestalt 'good continuity', and that this spread of attentional enhancement is predictive of the monkeys' behavioral performance in the curve-tracing task (Roelfsema *et al.*, 1998; Roelfsema and Spekreijse, 2001). An example of their data and of our model network's simulation of it are shown in Figure 2.

Thus, attention is influenced by the lateral connections that help to group together the smoothly connected curve segments – they provide the route along which attention spreads. Ito and Gilbert (Ito and Gilbert, 1999), also in a study of macaque V1, have shown that the converse direction of influence also holds, namely that lateral connections are influenced by attention: when a line segment is attended this changes the degree to which it is facilitated by a collinear neighbor.

By allowing top-down attentional and lateral contextual signals to reciprocally interact, cortex greatly extends the range of computations that it can implement. However, the fact that signals from different sources of origin can intermingle within the same cortical circuit raises the difficult problem of

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distinguishing the preattentive from the attentive, the external from the internal: cortex must be able to tell the difference between activity that conveys information about objects in the environment as opposed to activity that has arisen purely as a result of top-down cortical processing.

For attention, this problem is as follows: top-down attention can enhance or suppress the firing of cells that are already active, but if it were to produce above-threshold activity in the absence of any bottom-up retinal input, then the brain would be in danger of hallucinating; activity in early sensory cortex gets passed up to higher areas regardless of how it was caused, and these higher areas may have no means of telling the internally and externally created signals apart. It has, in fact, been elsewhere suggested how a breakdown in this process *can* lead to hallucinations, such as during the positive symptoms of schizophrenia (Grossberg, 2000b).

One possible way in which cortex could address this problem would be if it were to enforce the following simple rule: only those cells whose classical receptive fields (CRFs) receive direct bottom-up stimulation should be allowed to be active. However, the rich contextual processing that cortex implements would be crippled by such a rule, as can be illustrated with an example from the visual system: this would-be rule is disobeyed by neurons that respond to Kanizsa-type illusory contours (Kanizsa, 1979). Such neurons give above-threshold responses without having *any* visual stimuli within their CRFs, and are known to exist in V2 (von der Heydt *et al.*, 1984; Peterhans and von der Heydt, 1989) and possibly also in V1 (Lee and Nguyen, 2001). Responses to illusory contours induced by offset gratings have also been found in V1 (Redies *et al.*, 1986; Grosof *et al.*, 1993; Sheth *et al.*, 1996). Although the receptive fields of neurons responding to offset grating stimuli are not completely empty, since they contain line endings, they do not contain any stimuli that have the same orientation as the illusory contour itself.

Thus, cortex allows lateral contextual processing to produce internally generated, above-threshold activity in an unstimulated CRF (as in the case of Kanizsa-type illusory contours) but must forbid top-down attention from doing the same. And it must be able to distinguish between the signals that are generated by these two distinct forms of processing, while also allowing them to interact. The task of satisfying these seemingly conflicting constraints is what we call the *preattentive–attentive interface problem*.

This name summarizes the model hypothesis that laminar cortical circuits implement these constraints by sharing some circuits, namely the 'interface'. The full laminar architecture of the model, and how it allows the interface problem to be solved, are explained in detail in Section 3 below. In brief, the shared circuits help both to select the strongest preattentively formed groupings, while suppressing weaker groupings, and to let attention modulate this selection process. The selection of preattentively formed groupings is accomplished via an intracortical feedback loop between layers 2/3, 6, 4 and then back to 2/3. Attentive modulation is accomplished via an intercortical feedback loop from layer 6 of a higher cortical area to layer 6, 4 and 2/3 of a lower cortical area. The 'interface' occurs at layers 6-to-4, where attention can influence the groupings that are selected, as described in greater detail below. The model also proposes that there is a deeper reason why such a preattentive–attentive interface exists; namely, this interaction enables the cortex to develop and learn in a stable way (Grossberg, 1999a; Grossberg and Williamson, 2001). Thus the model proposes that the mechanisms that ensure stable development of cortical circuits in the infant strongly constrain the properties of perceptual learning, grouping and attention in the adult.

We suggest that the preattentive–attentive interface problem places tight constraints on the ways in which cortex can carry out attention and perceptual grouping, and that a solution in the face of such tight constraints provides the functional leverage needed to start interpreting what the cortical layers do. A more detailed discussion of the theoretical background to the model has already been given (Grossberg, 1999a), and fuller descriptions of the neurophysiological and psychophysical data that the model can simulate, along with the algorithmic details, have been provided previously (Grossberg and Raizada, 2000; Grossberg and Williamson, 2001; Raizada and Grossberg, 2001).

3. LAMINART Model Circuitry

The present model is called LAMINART because of its laminar structure and its embodiment of Adaptive Resonance Theory, or ART, mechanisms, as described in Section 6 below. The laminar architecture of the model is constructed out of two fundamental

Table 1
All references are to macaque monkey unless otherwise noted

Connection in model	Functional interpretation	Selected references
LGN→4	Strong, oriented LGN input	Blasdel and Lund (1983), Ferster *et al.* (1996, cat)
LGN→6	LGN input sharpened by 6→4 on-center off-surround	Blasdel and Lund (1983)
6→4 spiny stetlates	Modulatory on-center of the 6→4 on-center off-surround	Stratford *et al.* (1996, cat), Callaway (1998, p. 56)
6→4 inhibitory interneurons	Off-surround of the 6→4 on-center off-surround	McGuire *et al.* (1984, cat), Ahmed *et al.* (1997, cat)
4 inhib.int. →4 inhib.int.	Context-dependent normalization of off-surround inhibition	Ahmed *et al.* (1997, cat), Tamas *et al.* (1998, cat)
4→2/3 pyramidals	Feedforward of stimuli with bottom-up support	Fitzpatrick *et al.* (1985), Callaway and Wiser (1996)
2/3 pyr. →2/3 pyr.	Long-range collinear integration along RF axes	Bosking *et al.* (1997, shrew), Schmidt *et al.* (1997, cat)
2/3 pyr. →2/3 inhib.int.	Keep outward grouping subthreshold (bipole property)	McGuire *et al.* (1991), Hirsch and Gilbert (1991, cat)
2/3 inhib.int.→2/3 inhib.int.	Normalize 2/3 inhibition (2-against-1 part of bipole property)	Tamas *et al.* (1998, cat)
V1 2/3 pyr.→V2 layer 4	Feedforward of V1 groupings into V2	Van Essen *et al.* (1986), Rockland and Virga (1990)
V1 2/3 pyr.→V2 layer 6	Feedforward V1 groupings into V2 6→4 on-center off-surround	Van Essen *et al.* (1986, p. 470)
V1 layer6→LGN	Modulatory on-center, off-surround feedback	Sillito *et al.* (1994, cat), Montero (1991, cat)
Feedback routes into V1 layer 6		
V2 layer 6→V1 layer 1	Standard intercortical laminar feedback (Salin and Bullier, 1995, p.110)	Rockland and Virga (1989)
1→6 (within a layer 5 pyr.)	Corticocortical feedback into 6: Layer 5 pyr., apic.dend. in 1, axon in 6	Lund and Boothe (1975, Fig.7), Gilbert and Wiesel (1979, cat)
2/3→6	Boundary groupings feedback into 6→4 on-center off-surround	Blasdel *et al.* (1985, Fig.13), Kisvarday *et al.* (1989, Fig.7), Briggs and Callaway (2001)
1→5	Corticocortical feedback into 5: Layer 5 pyr. with apic.dend. in 1	Valverde (1985, Fig. 24o), Peters and Sethares (1991, p. 7)
2/3→5	Part of indirect 2/3→6 path	Lund and Boothe (1975, Fig. 8), Callaway and Wiser (1996)
5→6	Continuation of indirect routes into 6, via 5	Blasdel *et al.* (1985, Fig.17), Kisvarday *et al.* (1989, Fig. 7), Briggs and Callaway (2001)

building blocks: an on-center, off-surround circuit running from layer 6 to layer 4, and intrinsic horizontal connections in layer 2/3 which perform collinear integration and perceptual grouping. Each of these two subcircuits has assigned to it a well-defined functional role, and is constructed from model neurons with empirically determined connectivity and physiological properties, as summarized in Table 1. When these building blocks are connected together according to the known anatomy of V1 and V2, as shown in Figure 1, a cortical network is formed whose properties can be understood from the interactions of the functional subcircuits, but whose behavior is much richer than that of any subcircuit taken individually.

Attention in the model is mediated by a new mechanism that we call *folded feedback* (Grossberg, 1999a), whereby signals from higher cortical areas, and also the V1 supragranular layers, pass down into V1 layer 6 and are then 'folded' back up into the feedforward stream by passing through the layer 6→4 on-center, off-surround path (Fig. 1*b*), thus giving attention an on-center, off-surround form, enhancing attended stimuli and suppressing those that are ignored. This is consistent with psychophysical and neurophysiological evidence that attention has a facilitatory on-center and suppressive off-surround form (Downing, 1988; Steinman *et al.*, 1995; Caputo and Guerra, 1998; Mounts, 2000; Smith *et al.*, 2000; Vanduffel *et al.*, 2000).

A key prediction of the model is that the on-center of the 6→4 path is modulatory (or priming, or subthreshold), consistent with the finding that layer 4 EPSPs elicited by layer 6 stimulation are much weaker than those caused by stimulation of lateral geniculate nucleus (LGN) axons or of neighboring layer 4 sites (Stratford *et al.*, 1996), and also with the fact that binocular layer 6 neurons synapse onto monocular layer 4 cells of both eye types without reducing these cells' monocularity (Callaway, 1998, p. 56). We suggest that the on-center excitation is inhibited down into being modulatory by the overlapping and broader off-surround. Thus, although the center excitation is weak, the suppressive effect of the off-surround inhibition can be strong. Because attentional excitation passes through the 6→4 path before it affects visual processing, it inherits this path's properties: the attentional on-center is modulatory, able to enhance existing activity but only slightly to elevate neurons' baseline firing rates in the absence of visual input (Luck *et al.*, 1997), but the off-surround can select strongly against unattended stimuli. The model would still be supported if weak suprathreshold excitatory responses in layer 4 could be created by layer 6 stimulation, as long as these responses meet the crucial condition that they be too weak to cause suprathreshold groupings to occur within the horizontal connections of layer 2/3.

Several routes exist through which feedback from higher cortex can reach V1 layer 6, as shown in Table 1. Figure 1*b* illustrates the route whereby feedback signals pass into layer 1, where the majority of V2 feedback axons terminate (Rockland and Virga, 1989), and then stimulate the apical dendrites of layer 5 pyramidal cells whose axons send collaterals into layer 6 (Lund and Boothe, 1975; Gilbert and Wiesel, 1979), where the attentional signals are 'folded' back up into the 6→4 on-center off-surround. Reversible deactivation studies of monkey V2 have shown that feedback from V2 to V1 does indeed have an on-center, off-surround form (Bullier *et al.*, 1996), and moreover that the V1 layer whose activation is most reduced by cutting off V2 feedback is layer 6 (Sandell and Schiller, 1982). Another pathway whereby attention may act in the model is via layer 1 dendrites of layer 2/3 pyramidal cells and inhibitory interneurons. Like the pyramidal cells, these layer 2/3 interneurons also have dendrites that extend into layer 1 (Lund, 1987; Lund *et*

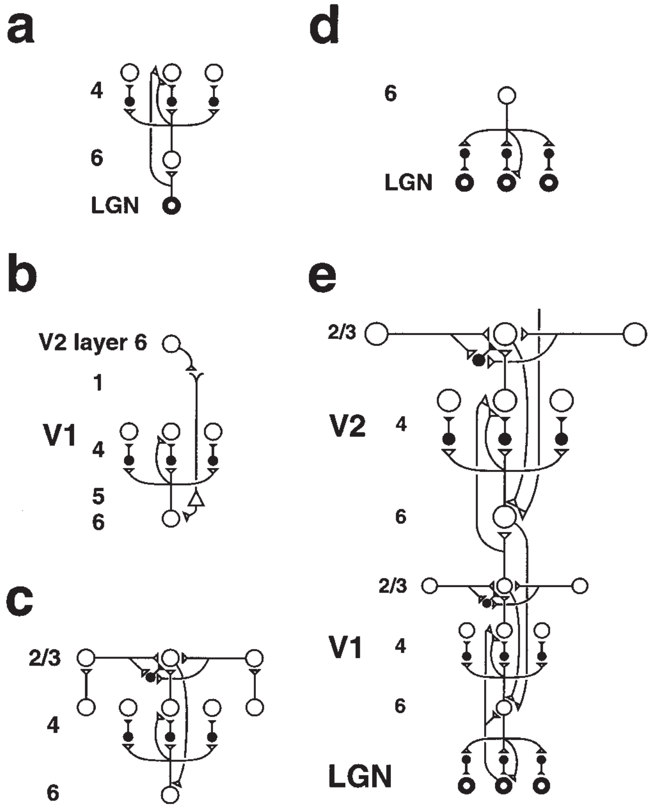

Figure 1. How known cortical connections join the layer 6→4 and layer 2/3 building blocks to form the entire V1/V2 laminar model. Inhibitory interneurons are shown filled-in black. (*a*) The LGN provides bottom-up activation to layer 4 via two routes. Firstly, it makes a strong connection directly into layer 4. Secondly, LGN axons send collaterals into layer 6, and thereby also activate layer 4 via the 6→4 on-center, off-surround path. Thus, the combined effect of the bottom-up LGN pathways is to stimulate layer 4 via an on-center off-surround, which provides divisive contrast normalization (Grossberg, 1973, 1980; Heeger, 1992) of layer 4 cell responses (see Appendix). (*b*) *Folded feedback* carries attentional signals from higher cortex into layer 4 of V1, via the modulatory 6→4 path. Corticocortical feedback axons tend preferentially to originate in layer 6 of the higher area and to terminate in the lower cortex's layer 1 (Salin and Bullier, 1995, p. 110), where they can excite the apical dendrites of layer 5 pyramidal cells whose axons send collaterals into layer 6. Several other routes through which feedback can pass into V1 layer 6 exist (see Table 1 for references). Having arrived in layer 6, the feedback is then 'folded' back up into the feedforward stream by passing through the 6→4 on-center, off-surround path (Bullier *et al.*, 1996). (*c*) Connecting the 6→4 on-center off-surround to the layer 2/3 grouping circuit: like-oriented layer 4 simple cells with opposite contrast polarities compete (not shown) before generating half-wave rectified outputs that converge onto layer 2/3 complex cells in the column above them. Like attentional signals from higher cortex, groupings that form within layer 2/3 also send activation into the *folded feedback* path, to enhance their own positions in layer 4 beneath them via the 6→4 on-center, and to suppress input to other groupings via the 6→4 off-surround. There exist direct layer 2/3→6 connections in macaque V1 (Briggs and Callaway, 2001), as well as indirect routes via layer 5 (Table 1). (*d*) Top-down corticogeniculate feedback from V1 layer 6 to LGN also has an on-center, off-surround anatomy, similar to the 6→4 path. The on-center feedback selectively enhances LGN cells that are consistent with the activation that they cause (Sillito *et al.*, 1994), and the off-surround contributes to length-sensitive (endstopped) responses that facilitate grouping perpendicular to line ends. (*e*) The entire V1/V2 circuit: V2 repeats the laminar pattern of V1 circuitry, but at a larger spatial scale. In particular, the horizontal layer 2/3 connections have a longer range in V2, allowing above-threshold perceptual groupings between more widely spaced inducing stimuli to form (Amir *et al.*, 1993). V1 layer 2/3 projects up to V2 layers 6 and 4, just as LGN projects to layers 6 and 4 of V1. Higher cortical areas send feedback into V2 which ultimately reaches layer 6, just as V2 feedback acts on layer 6 of V1 (Sandell and Schiller, 1982). Feedback paths from higher cortical areas straight into V1 (not shown) can complement and enhance feedback from V2 into V1. [Reproduced with permission from (Grossberg and Raizada, 2000).]

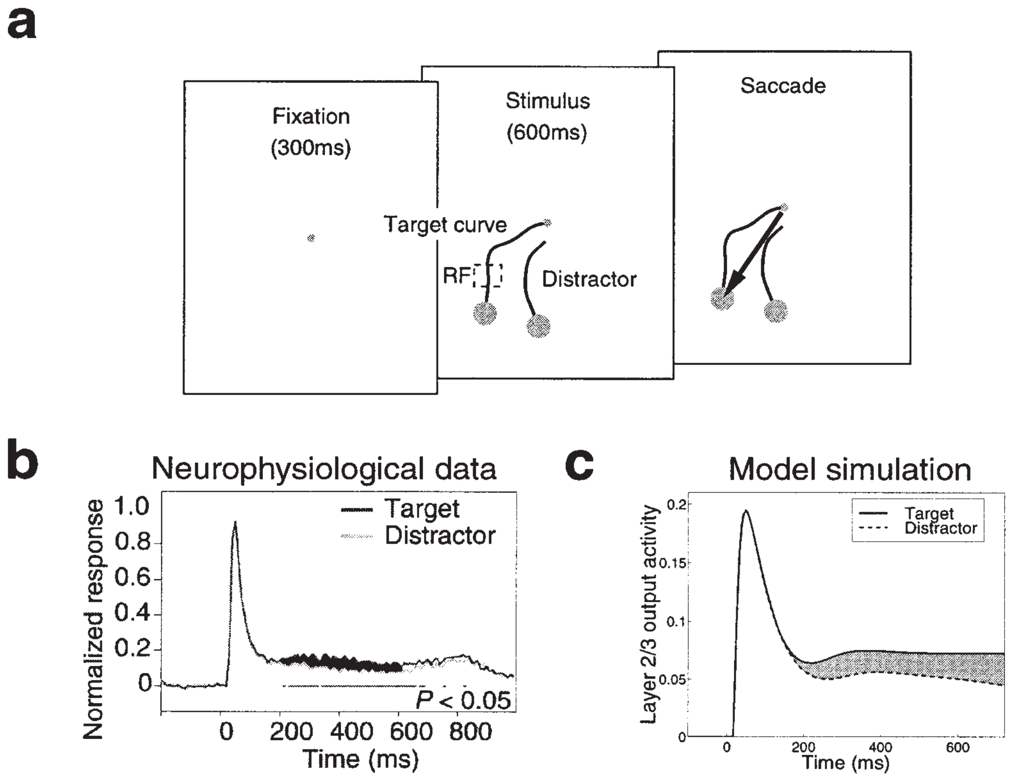

Figure 2. Spread of visual attention along an object boundary grouping, from an experiment by Roelfsema *et al.* (Roelfsema *et al.*, 1998). (*a*) The experimental paradigm. Macaque monkeys performed a curve-tracing task, during which physiological recordings were made in V1. A fixation spot was presented for 300 ms, followed by a target curve and a distractor curve presented simultaneously; the target was connected at one end to the fixation point. While maintaining fixation, the monkeys had to trace the target curve, then, after 600 ms, make a saccade to its endpoint. (*b*) Neurophysiological data showing attentional enhancement of the firing of a neuron when its receptive field (RF) lay on the target curve, as opposed to the distractor. Note that the enhancement occurs ~200 ms after the initial burst of activity. Further studies have indicated that the enhancement starts later in distal curve segments, far from the fixation point, than it does in proximal segments, closer to fixation (Roelfsema and Spekreijse, 1999). This suggests that attentional signals propagate along the length of the target curve. [Parts (*a*) and (*b*) adapted with permission from (Roelfsema *et al.*, 1998).] (*c*) Model simulation of the Roelfsema *et al.* data. [Reproduced with permission from (Grossberg and Raizada, 2000).] See the main text for explanation of network behavior.

al., 1988; Lund and Wu, 1997). Thus, this pathway is predicted to have a modulatory effect on layer 2/3 pyramidal cells due to the balance of excitation and inhibition, similar to the balance that keeps the layer 6→4 on-center subthreshold. This possible layer 1→2/3 attentional pathway has been implemented and explored by Raizada and Grossberg (Raizada and Grossberg, 2001).

We suggest that the mechanism of folded feedback is also used to help select the final layer 2/3 grouping. If the visual information coming into the brain is unambiguous, then the correct groupings could form due to the first incoming wave of activation from layer 4, to layer 2/3, and then across layer 2/3 horizontal connections. These groupings can then output directly to higher cortical areas, allowing rapid recognition of a visual scene with the first feedforward sweep of activation (Thorpe *et al.*, 1996). However, in response to scenes or images with multiple grouping possibilities, the initial groupings that are formed in layer 2/3 may need to be pruned to select those that are correct. Like attentional signals from higher cortex, the groupings that start to form in layer 2/3 also feed back into the 6→4 path (Fig. 1*c*), to enhance their own positions in layer 4 via the 6→4 on-center, and to suppress input to other groupings via the 6→4 off-surround. Before this selection process takes place, the mutual competition between several grouping possibilities can keep the amplitudes of the grouping cells in layer 2/3 less active than when only a single grouping exists. Thus outputs from layer 2/3 are delayed while the selection and enhancement process takes place via interlaminar feedback. As the selection is made, activities of layer 2/3 cells in the winning groupings are enhanced, and outputs from these cells are facilitated.

What is the anatomical substrate of this interlaminar grouping-selection process? There exist direct layer 2/3→6 connections in macaque V1 (Blasdel *et al.*, 1985; Kisvarday *et al.*, 1989; Briggs and Callaway, 2001), as well as indirect routes via layer 5 (Table 1). In the model, this cooperative–competitive interaction between layer 2/3 groupings, via layer 2/3→2/3 horizontal interactions and layer 2/3→6→4→2/3 interlaminar feedback, causes the strongest groupings to be selected, completed and coherently bound together, while it suppresses weaker group- ings, ungrouped distractors and noise. The selected groupings maintain their sensitivity to analog properties of of the inputs that initiated the grouping process. Achieving such analog coherence is another accomplishment of the cortical layers (Grossberg, 1999a). Interlaminar feedback also binds cells across the cortical layers into functional columns (Mountcastle, 1957).

The fact that both attention and perceptual grouping share the properties of enhancing weak stimuli, and of suppressing signals from nearby rival inputs, can thus be parsimoniously explained by the hypothesis that both processes share the 6→4 folded feedback path. This laminar architecture also resolves the preattentive–attentive interface problem described above, since despite their shared properties and coexistence side-by-side within V1 and V2, attention and grouping behave quite

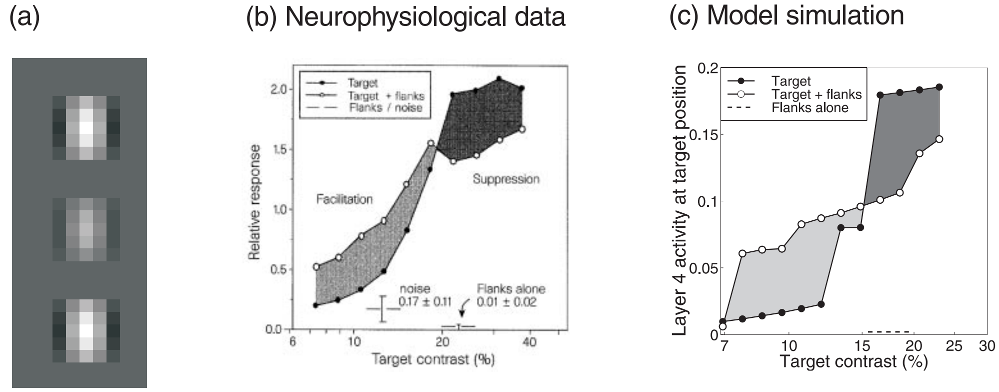

Figure 3. Contrast-dependent perceptual grouping in primary visual cortex. (*a*) Illustrative visual stimuli. A variable-contrast oriented Gabor patch stimulates the classical receptive field (CRF), with collinear flanking Gabors of fixed high contrast outside of the CRF. The stimulus shown here, based on those used by Polat *et al*. (Polat *et al*., 1998), was presented to the model neural network. (*b*) Neural responses recorded from cat V1. The collinear flankers have a net facilitatory effect on weak targets that are close to the cell's contrast-threshold, but they act to suppress responses to stronger, above-threshold targets. When the flankers are presented on their own, with no target present, the neural response stays at baseline levels. [Reproduced with permission from (Polat *et al*., 1998).] (*c*) Model simulation of the Polat *et al*. data. [Reproduced with permission from (Grossberg and Raizada, 2000).] See the main text for explanation of network behavior.

differently in parts of visual space where there is no bottom-up visual stimulus. Above-threshold boundary groupings *can* form over regions with no bottom-up support, e.g. illusory contours. These groupings form in layer 2/3. However, the top-down attentional signals enter layer 2/3 by first passing through pathways in which a balance of overlapping excitation and inhibition damps down the attentional feedback into being subthreshold, or priming. Thus, attention can only modulate layer 2/3, but cannot on its own cause above-threshold activation, and its internal/external problem is thereby resolved.

4. Explaining Neurophysiological Data Using the Laminar Architecture

Grossberg and Raizada have presented simulations of several neurophysiological and psychophysical data sets using the LAMINART model (Grossberg and Raizada, 2000; Raizada and Grossberg, 2001), including those from a number of other studies (Knierim and Van Essen, 1992; De Weerd *et al.*, 1999; Reynolds *et al.*, 1999). Here we summarize two different simulations which especially illustrate the mechanistically rich and testable types of explanation that the laminar framework allows. The first is a simulation of the study by Roelfsema *et al.* (Roelfsema *et al.*, 1998), which showed how top-down attentional enhancement in V1 can laterally propagate along a traced curve. The second is of the study by Polat and co-workers (Polat *et al.*, 1998), who showed contrast-sensitive perceptual grouping, also in V1.

A key design issue underlying the model's architecture concerns how attention and perceptual grouping interact (the preattentive–attentive interface problem, described above). Indeed, the model proposes that visual cortex is not just a feedforward filter, as has been classically proposed (Hubel and Wiesel, 1977), but is, among other things, a system designed to dynamically bind together distributed data into coherent groupings that can be actively modulated by higher-order, top-down constraints. Thus, a crucial test of the model is presented by the study by Roelfsema *et al.* (Roelfsema *et al.*, 1998) of activity in macaque V1 during performance of a curve-tracing task. This experiment provided evidence that attentional enhancement can propagate between neurons that represent different segments of a smooth curve. Their data and the model network's simulation of it are shown in Figure 2. Note that responses to the target curve are enhanced with respect to the distractor, but not until after a time delay of ~200 ms after stimulus onset. In the simulation, attentional signals were spatially directed only to the end of the target curve that corresponds to the fixation point. Attention in the model took the form of a two-dimensional Gaussian of activity fed back into V1 layer 6, starting simultaneously with the onset of the visual stimulus itself. This attentional activity passed into the modulatory layer 6→4 path (Fig. 1*b*), thereby strengthening the representation of the the end of the traced curve in layer 4, which in turn strengthened layer 2/3, where the extra activity propagated through intrinsic horizontal connections (Fig. 1*c*) along the boundary representation of the curve. The delayed onset of the enhancement in the model, which is also observed in the experimental data, arises because of the time taken for attentional signals to propagate laterally from their starting point at the end of the curve to the distal point on the curve, well outside the attentional on-center, from where the recorded activity was measured. Note that attentional feedback of the same strength as used here produced only subthreshold layer 2/3 excitation in a crucial control condition with attention presented in the absence of a bottom-up stimulus. This control also held for all the other simulations performed.

The next simulation is of the finding by Polat *et al.* (Polat *et al.*, 1998) of contrast-sensitive perceptual grouping in cat primary visual cortex (Fig. 3). The authors found that neural responses to a low-contrast target Gabor patch were facilitated when collinear flanking Gabor stimuli were added outside the receptive field, but that the flankers tended to suppress responses to Gabors that were of high enough contrast to cause above-threshold responses on their own. Similar results were obtained in a number of other studies (Toth *et al.*, 1996; Sengpiel *et al.*, 1997; Kapadia *et al.*, 2000). As shown in Figure 3*c*, the model neurons also exhibit this behavior. The flankers exert both excitatory and inhibitory effects on the neurons whose receptive fields contain the target. Long-range horizontal axons in V1 layer 2/3, which link neurons with collinear receptive fields (see Fig. 1c), carry excitation laterally from the flankers to the target. In V2 layer 2/3, this collinear facilitation has a longer range than it does in V1 (Fig. 1*e*), and a suprathreshold grouping forms between the two flankers, even when the target is absent or weak. The V2 grouping sends feedback via V2 layer 6 into V1, thus priming the V1 representation of the strip of space between the flankers, in particular the position of the target. This prime passes through the modulatory V1 layer 6→4 folded feedback path, therefore producing only subthreshold excitation in V1 layers 4 and 2/3 (the 'Flanks alone' condition in Figure 3). Because of this top-down and lateral excitation, not as much bottom-up activity need come from the target itself for it to excite cells supraliminally. Thus, the flankers act to reduce the cells' target-contrast threshold, raising the low-contrast section of the curve plotting neural-response versus target-contrast when the flankers are present.

However, the target also receives layer 6→4 off-surround inhibition from the flankers, which acts as a less-specific 'lateral masking', as opposed to the collinear facilitatory grouping carried by layer 2/3. This inhibition has a divisive, shunting effect (Grossberg, 1973, 1980; Heeger, 1992) on the target neurons, with the consequence that equal increases in target contrast cause smaller rises in activity when the flankers are present than when the target is presented on its own. Thus, when the flankers are present, the slope of the neural-response versus target-contrast curve is reduced; the flankers-present response curve starts off higher (the flankers are net facilitatory), but then it rises more slowly and is overtaken by the flankers-absent curve when the isolated target exceeds threshold (the flankers become net suppressive), as found experimentally by Polat *et al*. (Fig. 3*a*). This 'cross-over' behavior occurs in layers 4 and 2/3 of the model V1. Note that in the model, as in the physiological data, the point at which the curves cross is determined by the threshold of the recorded simple or complex cell itself, not by the threshold of inhibitory interneurons that synapse onto it, as is postulated by other models (Stemmler *et al.*, 1995; Li, 1998; Somers *et al.*, 1998).

5. Possible Relations to Laminar Architecture in Other Cortical Areas

Perhaps the most striking aspect of the six-layered cortical architecture is its strong degree of uniformity across cortical areas and across mammalian species. This raises the question of whether the laminar framework that we propose for V1 and V2 might provide a fruitful starting point for investigating other types of cortex. Some indications are promising, in particular the fact that long-range intrinsic horizontal connections in layer 2/3 appear to be a general feature of many different cortical areas. However, many important questions remain to be answered, not only about the laminar anatomical connections, but especially about their physiological behavior and possible functional roles. Thus, across cortex, investigating the functional role of laminar circuitry presents an important research opportunity, especially given some of the newly available experimental techniques that are discussed in Section 8.1 below. The LAMINART model presented here contributes to an emerging framework of hypotheses against which the empirical results can be compared.

5.1 The Six-layered Architecture of Isocortex

Before discussing the laminar circuity of individual cortical areas, the generality of the six-layered structure, and exceptions to it, will briefly be reviewed. This generality can be considered from two vantage points: across species and across cortical areas.

Across mammalian species, the area whose architecture has been most extensively studied comparatively is primary visual cortex. Its characteristic six-layered structure is present in all mammals, including rats, squirrels and tree shrews (Northcutt and Kaas, 1995), suggesting that the six layers were already present in a shared evolutionary ancestor. The subdivisions of the individual layers are more variable across species, with the most prominent examples being the magnocellular and parvocellular sublayers, which emerge only in primates. The model presented here discusses mainly the boundary-processing stream of parvocellular cortex. In future work, the model could be extended by also including the magnocellular and the surface-processing streams of cortex. The relationship of this model to a broader class of models of form and motion processing is discussed in Section 7 below.

Across cortical areas, those that exhibit the characteristic six-layered architecture are classed as 'isocortex' (Bowden and Martin, 1995; Northcutt and Kaas, 1995). However, not all cortical regions are six-layered isocortex. Those that have fewer than six layers are called 'allocortex', which includes structures such as the hippocampus and the periamygdaloid area. There also exist transitional regions: the 'proisocortex' which borders true isocortex, lacks a layer 4, and includes Brodmann areas 24, 25 and 32 (Barbas and Pandya, 1989), and the periallocortex which borders allocortex, also lacks a layer 4 and includes areas neighboring the corpus callosum, as well as entorhinal cortex (Krimer *et al.*, 1997; Rempel-Clower and Barbas, 2000). In the prefrontal cortices, the lateral and rostral orbitofrontal areas have six layers, whereas layer 4 in the caudal orbitofrontal areas is either absent (agranular periallocortex) or only incipient [dysgranular proisocortex (Barbas and Rempel-Clower, 1997; Rempel-Clower and Barbas, 2000)]. Primary motor cortex constitutes an interesting intermediate case: adult primates lack a granular layer 4 (Stepniewska *et al.*, 1993), although this layer is present in adult rats (Skoglund *et al.*, 1997). Human newborns also have a layer 4, which gradually disappears postnatally (Amunts *et al.*, 1995).

These non-isocortical regions constitute only a relatively small fraction of the whole cortical sheet, with the great majority of cortical regions being six-layered isocortex, including visual, auditory and somatosensory cortices, and many prefrontal and frontal areas.

Another aspect of the generality of the six-layered structure of cortex is its relation to the laminar pattern of corticocortical projections. Felleman and Van Essen (Felleman and Van Essen, 1991) proposed a framework in which feedforward projections tend to originate primarily in the supragranular layers of the lower cortical area and to terminate in layer 4 of the higher area, and in which feedback connections tend to originate mostly in the infragranular layers of the higher area and to terminate in layer 1, and possibly also layer 6, of the lower area. Bilaminar patterns of origin and termination are also possible. Salin and Bullier (Salin and Bullier, 1995) added the observation that as two visual areas become further apart from each other in the cortical hierarchy, the tendency increases for corticocortical feedback axons preferentially to originate in layer 6 of the higher area and to terminate in the lower cortex's layer 1. The model of V1 and V2 that we present here is consistent with these observations, emphasizing the feedforward connections from V1 into V2 layers 4 and 6, and from V2 layer 6 into V1 layer 1.

Barbas and colleagues have extended and refined these studies of laminar connectivity, showing that in frontal and anterior temporal cortical areas the degree of laminar definition within an area is also predictive of the layers of termination and origin of corticocortical connections (Barbas and Rempel-Clower, 1997; Rempel-Clower and Barbas, 2000; Dombrowski *et al.*, 2001). In particular, a highly laminated area tends to project from layer 2/3 to layers 4–6 of an area with less laminar definition, and conversely a less laminated area tends to project from layers 5–6 to layers 1–3 of an area with greater laminar definition. This observation was made by Barbas with respect to more anterior cortices, but it is also consistent with the model of early visual cortex presented here, since V1, the cortical area with the greatest laminar definition of all, projects forward from layer 2/3 and tends to receive feedback into its layer 1.

Thus, given the significant generality of the the six-layered architecture, the possible roles across cortical areas of intrinsic horizontal and interlaminar connections will now be briefly reviewed.

5.2 Horizontal Intrinsic Connections

As was described in Section 3 above, our model proposes that long-range horizontal intrinsic axons in layer 2/3 support the perceptual grouping of collinear oriented elements, by linking complex cells with similar preferred orientations. In low-level visual cortex, significant experimental evidence supports this hypothesis, including studies of cats (Gilbert and Wiesel, 1989; Schmidt *et al.*, 1997), tree shrews (Fitzpatrick, 1996; Bosking *et al.*, 1997), squirrel monkeys and owl monkeys (Sincich and Blasdel, 2001). The novel contributions of this laminar model are to suggest how groupings start to form in layer 2/3 by using a combination of monosynaptic horizontal excitation and disynaptic inhibition, how these groupings send folded feedback into the layer 6→4 on-center, off-surround pathway, how top-down cortical feedback from higher areas such as V2 can influence layer 2/3 groupings, also through the folded feedback path, and, as is described in Section 6 below, how these mechanisms help to ensure stable cortical development and learning. Figure 3 illustrates how these laminar circuits can account for contrast-sensitive contextual effects, in which surrounding visual stimuli can excite a low-contrast center stimulus, but then have a net inhibitory effect on a center stimulus that is high contrast.

Thus, possible parallels in other, non-visual cortical areas would include supragranular long-range horizontal intrinsic axons connecting neurons whose response properties are similar to each other, and evidence that these contextual interactions tend to facilitate low-intensity stimuli but to suppress those that are of high intensity.

Significant evidence relating horizontal connections to the properties of the columns that they interconnect has recently been discovered in primary auditory cortex. Read and co-workers (Read *et al.*, 2001) showed that intrinsic horizontal axons in the supragranular layers connect subregions that are selective for similar frequency bandwidths. Previous studies had sought, but been unable to find, links between these horizontal connections and the spatial organization of auditory cortical neurons' preferred frequency, or their degree of binaurality [reviewed by Read *et al.* (Read *et al.*, 2001)]. An important insight into the mechanisms underlying the growth of these auditory horizontal connections was provided by Sharma and co-workers, who artificially rewired ferret auditory cortex so that it received visual input (Sharma *et al.*, 2000). The reconfigured auditory cortex was found to exhibit a structure resembling V1 orientation columns, and, crucially, the intrinsic horizontal connections were found to be patchy and anisotropic, again similar to the pattern found in V1. Thus, the growth of auditory horizontal connections is strongly influenced by the pattern of afferent neural activity, as is the case in visual cortex (Ruthazer and Stryker, 1996; Galuske and Singer, 1996). The LAMINART model has simulated how horizontal connections develop in visual cortex in response to afferent neural activity and shows how the rules that ensure stable development lead to properties of grouping and attention in the adult (Grossberg and Williamson, 2001); see the discussion below.

In macaque inferotemporal cortex, some preliminary evidence suggesting that long-range horizontal connections might link columns that respond to similar higher-order object features has recently been presented by Tanifuji *et al.* (Tanifuji *et al.*, 2001). Inferences from (non-laminar) neural models of how perceptual categories are learned suggests that long-range horizontal connections in inferotemporal cortex and possibly also prefrontal cortex (PFC) may play a role in building three-dimensional object representations (Bradski and Grossberg, 1995; Carpenter and Ross, 1995). The intrinsic axon collaterals of supragranular pyramidal neurons in monkey PFC spread horizontally for several millimeters and give rise to discrete, stripe-like clusters of axon terminals which span layers 1–3 (Levitt *et al.*, 1993), and which synapse mostly onto spiny, and hence presumably excitatory, neurons (Melchitzky *et al.*, 1998). The pyramidal neurons that originate these long-range axons also appear to be arranged in stripes (Kritzer and Goldman-Rakic, 1995). It has been suggested that these reciprocal long-range connections may implement reverberating excitatory circuits for working memory, maintaining the firing of prefrontal neurons in the absence of external stimulation (Goldman-Rakic, 1995). An alternative possibility is that working memories are stored by vertical intracortical feedback pathways, such as those between layers 6, 4, and 2/3, while horizontal connections may group the items that are stored in working memory into 'sequence chunks', such as those that represent words in language (Grossberg and Myers, 2000). Clearly, there is tremendous scope for further studies of the functional roles of these laminar circuits. The dual roles of grouping spatially distributed information and of implementing reverberatory working memory loops are by no means mutually opposed, and indeed may be complementary aspects of a single computational process.

We now consider possible analogs in non-visual cortices of intensity-dependent, contextual interactions of the sort shown in visual cortex by Polat *et al.* (Polat *et al.*, 1998) and other groups, and simulated by the laminar circuits of our model. As far as we are aware, the only non-visual case of this phenomenon that has so far been demonstrated is in the somatosensory domain, namely in rodent barrel cortex. Like visual cortex, barrel cortex also contains long-range horizontal connections, which develop most profusely in the supragranular layers (B. Miller *et al.*, 2001). These intrinsic connections are thought to support the integration of signals from spatially neighboring whisker barrels. Evidence that this spatial integration is intensity-dependent has been summarized by Moore *et al.* (Moore *et al.*, 1999), especially in their Figure 6. When a vibrissa is weakly stimulated, stimulation of surrounding vibrissae facilitates the response at the center. However, when the center vibrissa is strongly stimulated, surround stimulation has a net inhibitory effect on it. This 'cross-over' from facilitation to inhibition with increasing center-stimulus intensity is directly analogous to the visual case. An interesting open research question is whether corresponding phenomena might occur in the cortices of other sensory modalities, and whether laminar circuits that are analogous to those proposed in the LAMINART model of visual cortex might underlie these intensity-dependent contextual effects.

In motor cortex, supragranular horizontal connections also carry excitation across several millimeters of cortex (Aroniadou and Keller, 1993). Their function is currently unknown, although Donoghue and colleagues have produced evidence showing that they participate in skill-learning, with the learning inducing LTP (Rioult-Pedotti *et al.*, 1998). The questions of what types of information these connections might be carrying, and of how this lateral flow of signals might interact with top-down attention feedback, are ripe for future research. In considering how motor cortex may be organized, one needs to keep in mind other modeling results which suggest that different cortical streams may be organized to realize complementary processing goals (Grossberg, 2000a). In particular, some processes in the 'What' cortical processing stream (Ungerleider and Mishkin, 1982), where the boundary-grouping parvocellular cortex is situated, may be complementary in their organization to processes in the 'Where' cortical processing stream, where motor cortex is situated. How these complementary processes are reflected within the underlying laminar cortical circuitry remains to be worked out.

5.3 Interlaminar Circuitry

Although significant progress has been made in interpreting horizontal intralaminar circuitry, the functional roles of vertical interlaminar connections in non-visual areas have been explored only to a limited extent. As was argued above, analyzing the functional constraints that might govern the implementation of specific types of processing in the laminar circuitry can provide a crucial guide towards starting to interpret the complex tangle of connectivity. The LAMINART model provides such a guide for perceptual cortices through its analysis of how perceptual grouping and top-down attention interact. An analysis of the functional constraints on how eye movement plans are learned and interact with reactive movement cues has led to a model of how the laminar circuits in prefrontal cortex interact with the basal ganglia and superior colliculus during eye movement control. For details, the reader is referred to Brown *et al.* (Brown *et al.*, 2000).

Given that sensory cortices of all modalities must deal in some way or other with the preattentive–attentive interface problem, i.e. the challenge of integrating top-down attentional feedback with lateral contextual processing, we hypothesize that some commonalities with the V1 and V2 architecture proposed here may emerge. In particular, the mechanism of sending folded feedback into a feedforward pathway with a powerful off-surround and a modulatory on-center may have computational utility in a wide range of sensory contexts, over and above that of allowing top-down visual attention to influence collinear perceptual grouping. However, laminar computational theories must also respect the differences that exist between cortical areas of different sensory modalities. For example, Smith and Populin have provides evidence of an important structural difference between auditory and visual cortex in the cat: whereas visual cortex receives thalamic input in a layer 4 consisting mostly of spiny stellate cells, auditory cortex appears to receive its input mostly onto pyramidal cells in layer 4 and lower layer 3 (Smith and Populin, 2001).

6. The Role of Top-down Corticocortical Feedback: Attention, Adaptive Resonance and the Stability–Plasticity Dilemma

In presenting the reasoning underlying the model architecture in Section 3 above, it was described how an analysis of the seemingly conflicting functional constraints on perceptual grouping and top-down attention can help to provide a foothold for starting to interpret the tangled laminar circuitry of visual cortex. However, a more fundamental consideration also motivates the model, namely seeking to understand how cortical circuits develop and learn in a stable way through time.

Adaptive resonance theory, or ART (Grossberg, 1980, 1999b, 1995; Pollen, 1999), is a cognitive and neural theory which addresses a general problem that faces all adaptive brain processes, namely the *stability–plasticity dilemm*a: how can brain circuits be plastic enough to be rapidly fine-tuned by new experiences, and yet simultaneously stable enough that they do not get catastrophically overwritten by the new stimuli with which they are continually bombarded?

The solution that ART proposes to this problem is to allow neural representations to be modified only by those incoming stimuli with which they form a sufficiently close match. If the match is close enough, then learning occurs. Precisely because the match is sufficiently close, this learning will be a fine-tuning of the existing representation, rather than a radical overwriting. If the active neural representation does not match with the incoming stimulus, then the neural activity will be extinguished and hence unable to cause plastic changes. The extinguishing of the initially active representation creates an opportunity for some other representation to become active instead. This in turn will either give rise to a match, thereby allowing learning, or a non-match, causing the process to repeat until eventually either a match is found or the incoming stimulus causes a totally new representation to be formed.

The connection with the model of top-down attention described in this paper is as follows: the mechanism that implements the matching process is top-down attentional feedback directed to behaviorally relevant sensory stimuli. The ART model predicts that modulatory on-center, off-surround, top-down attentional signals should exist, whose role is to select and enhance behaviorally relevant, bottom-up sensory inputs (match), and suppress those that are irrelevant (non-match). Mutual excitation between the top-down feedback and the bottom-up signals that they match strengthens, synchronizes and maintains existing neural activity long enough for synaptic changes to occur. Thus, attentionally relevant stimuli are learned, while irrelevant stimuli are suppressed and hence prevented from destabilizing existing representations. [For a more extensive review see (Grossberg, 1999b).]

Thus, the folded feedback layer 6→4 modulatory on-center, off-surround attentional pathway in the present model can be thought of as an implementation of ART matching in cortical laminar circuitry. The claim that bottom-up sensory activity is *enhanced* when matched by top-down signals is in accord with an extensive neurophysiological literature showing the facilitatory effect of attentional feedback (Luck *et al.*, 1997; Roelfsema *et al.*, 1998), but not with models in which matches with top-down feedback cause suppression (Mumford, 1992; Rao and Ballard, 1999). The ART proposal raises two key questions:

1. Does top-down cortical feedback have an on-center, off-surround structure?
2. Is there evidence that top-down feedback controls plasticity in the area to which it is directed?

The on-center, off-surround structure of top-down cortical feedback has been demonstrated in the visual system both for V2→V1 feedback (Bullier *et al.*, 1996) and for V1→LGN feedback (Sillito *et al.*, 1994). Nobuo Suga and colleagues have shown that feedback from auditory cortex to the medial geniculate nucleus (MGN) and the inferior colliculus (IC) also has an on-center, off-surround form (Zhang *et al.*, 1997). Most recently, Temereanca and Simons have produced evidence for a similar feedback architecture in the rodent barrel system (Temereanca and Simons, 2001).

A more stringent test of the ART claim is that top-down feedback should control plasticity. Psychophysically, the role of attention in controlling adult plasticity and perceptual learning was demonstrated by Ahissar and Hochstein (Ahissar and Hochstein, 1993). However, there is also physiological evidence. Gao and Suga (Gao and Suga, 1998) found that acoustic stimuli caused plastic changes in the inferior colliculus of bats only when the IC received top-down feedback from auditory cortex. The authors also found that this plasticity is enhanced when the auditory stimuli were made behaviorally relevant, in accord with the ART proposal that top-down feedback allows attended, i.e. relevant, stimuli to be learned, while suppressing unattended irrelevant ones. Evidence that cortical feedback also controls thalamic plasticity in the somatosensory system has been found by Nicolelis and colleagues (Krupa *et al.*, 1999) and by Parker and Dostrovsky (Parker and Dostrovsky, 1999). A concise review of these findings has been provided by Kaas (Kaas, 1999).

Another possible role of these feedback connections might be to synchronize the firing patterns of higher and lower cortical areas. Given that 'cells that fire together wire together', synchronous firing of this sort would further increase the ability of the mutually excitatory resonant activity caused by ART matching to allow synaptic plasticity and learning to take place. It has elsewhere been shown that variants of the ART model are capable of rapidly synchronizing their emergent states during both perceptual grouping and attentional focusing (Grossberg and Somers, 1991; Grossberg and Grunewald, 1997). An excellent recent discussion of top-down cortical feedback, synchrony and their possible relations to the ART model is given by Engel *et al.* (Engel *et al.*, 2001).

The hypothesis that attentional feedback exerts a controlling influence over plasticity in sensory cortex does not imply that unattended stimuli can never be learned. Indeed, it is clear that plasticity must be allowed to take place during early development, before top-down attention has even come into being, as is discussed by Grossberg (Grossberg, 1999a). During development, plastic changes in cortex are driven by stimuli that occur with high statistical regularity in the environment (Grossberg and Williamson, 2001), a process that can continue to fine-tune sensory representations in adulthood (Watanabe *et al.*, 2001). Attentional control of plasticity is not required for overseeing such fine-tuning, but rather for the prevention of radical overwriting that would upset the balance between stability and plasticity.

Given that there is experimental support for the ART prediction that top-down attention plays a matching role which helps to control cortical plasticity, it remains necessary to explain other data which, at the outset, seem to conflict with this prediction. In particular, how can pre-attentive groupings form over positions that receive no bottom-up inputs, without destabilizing cortical development and learning?

As was described above, the ART matching rule has three aspects: (i) incoming sensory signals that receive matching top-down excitatory feedback should be enhanced; (ii) non-matching inputs that do not receive excitatory feedback should be suppressed; and (iii) top-down feedback on its own should be only modulatory, i.e. unable to produce above-threshold activity in the lower area in the absence of incoming bottom-up signals. The conceptual challenge is this: if ART matching is needed to stabilize cortical development and learning, and if ART matching requires that suprathreshold activation can occur only where there are bottom-up inputs, then does not the existence of illusory contours contradict the ART matching rule, since such groupings form over positions that receive no bottom-up inputs, and do not seem to destabilize cortical development or learning? Here is where the laminar cortical solution of the preattentive–attentive interface problem plays a key role. When a horizontal grouping starts to form in layer 2/3, it also activates the interlaminar feedback pathway from layer 2/3 to the modulatory on-center, off-surround network from layer 6 to 4. This feedback pathway helps to select which cells will remain active to participate in a winning grouping. But this is the same network that ART requires attention to use when it stabilizes cortical development and learning. In other words, the layer 6-to-4 selection circuit, which in the adult helps to choose winning groupings, helps to assure in the developing brain that the ART matching rule holds at every position along a grouping. Because the matching rule holds, only the correct combinations of cells can 'fire together and wire together', and hence stability is maintained. Intracortical feedback via layers 2/3→6→4→2/3 can realize this selection process even before intercortical attentional feedback can develop. This property is sometimes summarized with the phrase: 'The pre-attentive grouping is its own attentional prime' (Grossberg, 1999a).

7. Relation to Other Models of Visual Cortex

The principal novel contribution of the model presented here is that it proposes specific functional roles for the layers of visual cortex, and for the intracortical and intercortical projections that connect them. Other proposed models have not addressed these issues of laminar circuitry. A less obvious contribution is that this model, as far as we are aware, is the first to formulate and to attempt to resolve the preattentive–attentive interface problem, which was described in Section 2 above: cortex, and models of cortex, must allow perceptual grouping to produce internally generated, above-threshold activity in a classical receptive field that does not contain any visual stimuli (as occurs in illusory contour completion) but must forbid top-down attention from doing the same. Our model proposes that the key step to solving this problem is to force attention to pass through a modulatory laminar circuit *en route* to layer 2/3, the layer where perceptual grouping starts, with the result that attention can provide a subthreshold boost to groupings formed by layer 2/3 cells, but is unable to directly drive them above threshold.

If a model of visual cortex incorporates top-down attentional feedback without implementing perceptual grouping, then it avoids the the preattentive–attentive interface problem. However, it avoids the problem at a cost: the model leaves out the contextual processing that enables cortex to segment cluttered visual scenes with such success. Examples of such models have been given by a number of authors (Harth *et al.*, 1987; Mumford, 1992; Olshausen *et al.*, 1993; Ullman, 1995; Tsotsos *et al.*, 1995; Usher and Niebur, 1996; Rao and Ballard, 1999). If a model of this sort were to be extended to include perceptual grouping, then the interface problem would become inescapable. As soon as contextual processing is incorporated that is rich enough to complete illusory contours, then the model must somehow provide a mechanism for distinguishing between internally and externally generated signals: if a neuron with an empty classical receptive field is firing above threshold, then is that neuron creating hallucinatory signals, or is it performing the useful task of completing an object's contour? The laminar framework of our model allows it to give an answer to that question: such a neuron is hallucinating if it is an excitatory cell in layer 4, but it is helping to form a grouping if it is in layer 2/3.

Note that this problem arises only if the perceptual grouping causes illusory contours to form. Models of grouping that incorporate lateral facilitation without allowing groupings to bridge over retinally unstimulated visual space also avoid the preattentive–interface problem, but again at a cost. Above and beyond the simple empirical fact that illusory contours *do* cause above-threshold activity in cortex (von der Heydt *et al.*, 1984) and hence cannot be ignored, illusory contours also perform a crucial computational task which mere facilitation cannot: they can actively close incomplete boundaries, a process that requires that cells with unstimulated CRFs can nonetheless become active. This boundary closure can guide surface reconstruction, complete boundaries over visual gaps caused by the blind-spot and retinal veins, and also provide enhanced information for the recognition of partially occluded objects (Grossberg, 1994). Several other models of collinear grouping in V1 produce facilitation but not illusory contours, and hence are unable to capture this important aspect of cortical processing (Stemmler *et al.*, 1995; Li, 1998; Somers *et al.*, 1998; Yen and Finkel, 1998). Those models that do implement illusory contours either leave out any consideration of top-down cortical feedback (Williams and Jacobs, 1997; Heitger *et al.*, 1998), fail to capture the on-center, off-surround form of attention by treating top-down feedback as having a purely excitatory multiplicative effect (Neumann and Sepp, 1999), or treat 're-entrant' feedback signals from higher areas 'as if they were signals from real contours in the periphery entering via 4 . . .' (Finkel and Edelman, 1989, p. 3197), thereby creating the risk of perceptual hallucinations and unstable learning.

The model presented here proposes laminar neural substrates for attention and the representation of visual groupings, or boundaries, and extends a general theory of how boundary and surface representations interact in the visual system (Grossberg and Mingolla, 1985; Grossberg, 1994; Grossberg *et al.*, 1997): raw edge signals are pooled, sharpened and completed into closed boundaries, which are 'filled-in' by neural activity representing surface brightness and color. A full review (Grossberg, 1994; Pessoa *et al.*, 1998) of experimental evidence for this theory is beyond the scope of the current article, although particularly noteworthy are some recent neurophysiological (Lamme *et al.*, 1999) and psychophysical studies (Dresp and Grossberg, 1997; Elder and Zucker, 1998; Rogers-Ramachandran and Ramachandran, 1998). Two recent macaque studies have shown that V1 neurons respond to brightness and texture edges that are outside of their classical receptive field, with the latency of neural activity being an increasing function of distance between the edge and the receptive field center (Lee *et al.*, 1998, Fig. 18; Rossi *et al.*, 2001, Fig. 9). This is consistent with the existence of fast lateral filling-in of brightness signals in macaque V1, in the 50–100 ms timescale that has been observed psychophysically (Paradiso and Nakayama, 1991). The model proposed here implements only the boundary aspects of this process, rather than the surface color signals. Including the latter within the laminar framework, e.g. as horizontal interactions between cytochrome oxidase blobs in area V1, or between thin stripes in area V2, would constitute a promising possible future extension of the model. There are many other important aspects of visual cortex that could be included in future extensions of the model, including, among others: the magno- and parvocellular subdivisions of the cortical layers, spatial frequency analysis, and the role of layer 5. In fact, the LAMINART model has already been extended in a consistent way to explain and simulate how the laminar circuits of visual cortex may be used to simulate data about three-dimensional vision, including stereopsis, the perception of tilted and curved surfaces in three dimensions, and various lightness illusions (Howe and Grossberg, 2001; Swaminathan and Grossberg, 2001). A cortical model of motion segregation and integration has needed ART matching properties to explain data about motion capture (Chey *et al.*, 1997; Grossberg *et al.*, 2001), although this model has not yet been given a detailed laminar interpretation.

8. Laminar Models: Bridging the Gap Between Computational Principles and Testable Predictions

By seeking to propose specific functional roles for laminar circuits consisting of anatomically identified neurons and interneurons, computational models of the sort that we have presented here have the potential to engage in a close dialogue with empirical studies of cortex. Every function that the model proposes for a neural circuit constitutes a testable prediction. However, neurobiological detail in itself is not sufficient to bridge between theory and experiment: a computational model can be extremely detailed — e.g. a multi-compartmental model of ionic currents in a dendritic tree — without it necessarily casting any light on the *information processing* aspects of the neural activity. The model presented here seeks to address this problem by attempting to show how specific types of visual processing, in particular perceptual grouping and top-down attention, can be implemented in specific laminar circuits. That is, the model seeks to ask not only what patterns of neural activity might be found in the circuits of cortex, but also how this activity might help an organism to see.

Another novel aspect of the model proposed here is that it provides specific hypotheses about the functional roles of the connections *between* the cortical layers, rather than considering a single layer in isolation. The explanations that the model provides of the neurophysiological data by Roelfsema *et al.* (Roelfsema *et al.*, 1998), shown in Figure 2, and by Polat *et al.* (Polat *et al.*, 1998), shown in Figure 3, illustrate the importance of considering these interlaminar connections. Although the processing occuring within a single layer, e.g. layer 4 (K.D. Miller *et al.*, 2001), is interesting in itself, this forms only one part of the much richer set of computations that cortex performs with its feedforward, horizontal and feedback circuitry. Before presenting some examples of the testable predictions that are generated by the model, we will first discuss some recently developed experimental techniques that may offer new opportunities for investigating laminar function.

8.1 New Experimental Techniques for Probing Laminar Circuitry

A major practical impediment to enriched knowledge of the cortical layers' functionality is the fact that detailed knowledge of the laminar position of an electrode has traditionally required immediate histology, in order to reconstruct the locations of electrolytic lesions. Recent technical advances may allow the localization of recording sites over longer time periods, or even in the living animal, which is especially desirable given that animals can take many months to train if they are being used to study complex tasks. Snodderly and Gur (Snodderly and Gur, 1995) marked their electrode tracks using a fluorescent dye which persisted for several months after recording, thereby allowing the animal to be used for further experiments, rather than being used straight away for determining the laminar histology. Potentially more promising is the technique recently developed by Fung *et al.* (Fung *et al.*, 1998). They used small bursts of current to electrically deposit very small amounts of iron at the tip of the electrode while recording, and were able to reconstruct the position of the electrode non-invasively using high-field anatomical magnetic resonance imaging. In principle, this technique could be used to provide laminar physiological data in living animals. However, it remains to be seen whether the spatial resolution will be precise enough reliably to locate the electrode in a specific layer.

Among the very few studies that have produced laminar data from the sensory cortex of awake, behaving animals are recent experiments by Schroeder and colleagues (Mehta *et al.*, 2000a,b). They penetrated vertically through the cortex using an electrode array with multiple recording sites, allowing them to make current source density (CSD) and event-related potential (ERP) recordings simultaneously across the layers while their monkeys performed attentional tasks. Unfortunately, the electrodes used in these studies did not penetrate deeper than layer 5, and hence cannot cast light on our model's proposal that layer 6 plays a key role in implementing top-down attention. Also, CSD recordings are somewhat harder to relate to a circuit model than are single-unit recordings. Nonetheless, the general approach appears to be very promising, and could probably be used to directly test some of the experimental predictions that are outlined below.

Recent developments in laminar slice recordings, especially by Callaway and colleagues, have produced extremely informative data on the physiological efficacy of monosynaptic connections between neurons in different layers. In this technique, the cortical slice is bathed in caged glutamate (Kotter *et al.*, 1998) and a chosen cell is patch clamped so that it can be recorded intracellularly and subsequently stained to reveal its axonal and dendritic arbors (Dantzker and Callaway, 2000; Briggs and Callaway, 2001). Photostimulation with a laser releases the glutamate at any chosen location in the slice, causing a focal and low-intensity burst of neural excitation at that position. The neural response that this stimulation evokes in the clamped neuron is then recorded. By stimulating sequentially across the whole slice, a two-dimensional spatial map is produced of the physiological drive that each location exerts on the selected neuron. An example of the new types of information that are obtainable using this technique is the finding by Briggs and Callaway (Briggs and Callaway, 2001) of strong monosynaptic drive from layer 2/3 to layer 6 pyramidals whose axons arborize in layer 4Cβ. This pathway, whose existence is not apparent from anatomical studies alone (Callaway, 1998) is highly consistent with the folded feedback pathway predicted by our model, in which active perceptual groupings in layer 2/3 feedback back into layer 6, and from there into a layer 6→4 on-center, off-surround pathway. Previous studies using optical imaging of slice preparations had also produced interesting data on laminar patterns of excitation (Tanifuji *et al.*, 1994; Yuste *et al.*, 1997; Kohn *et al.*, 2000), but, as with the CSD recordings mentioned above, these maps of extensive activation across large populations of neurons are much harder to relate to circuit-level computations than are the precise maps of drive to a single-neuron that are permitted by the caged glutamate method. Thus it appears that these techniques, and doubtless others yet to be developed, are starting to create new opportunities for obtaining laminar neurophysiological data. Given the remarkable scope for novel experimentation in this area, our hope is that the model presented here might help to provide a computational framework that could motivate empirical work, especially for examining how 'higher order' visual processes such as attention and perceptual grouping might be implemented at the circuit level.

8.2 Testable Experimental Predictions

Given these exciting new experimental possibilities for investigating the functional roles of the cortical layers, we can now consider some of the testable neurophysiological predictions that follow from the model's laminar architecture. As was remarked above, by attempting to assign specific functional roles to anatomically delineated laminar circuits, the model makes itself much more directly testable than it would be if it kept to the level of computational abstraction. A very simple, but as yet untested, prediction of the model is that the layer 6→4 pathway should have a spatially on-center, off-surround structure. Studies of the effect of layer 6 on length-tuning in layer 4 (Grieve and Sillito, 1991a,b, 1995) are consistent with a spatial pattern of center excitation and surround inhibition, but did not test this specific issue directly. A core prediction about the layer 6→4 on-center in particular is that its excitation should be subthreshold: for example, intracellularly evoked layer 6 activity should modulate, but not drive, layer 4 spiny stellates and layer 2/3 pyramidals. The model proposes that attentional feedback into layer 6 passes into this modulatory 6→4 on-center to remain subthreshold in the absence of bottom-up visual input. Thus, it predicts that attentional elevation of a neuron's baseline firing rate when there is no stimulus in its receptive field, as observed by Luck *et al.* (Luck *et al.*, 1997), should cause above-threshold activation in layer 6, but below-threshold activation of layer 4 spiny stellates. Note that Luck *et al.* found this baseline elevation in V2 but not in V1. Since we suggest that the laminar mechanisms of attention are similar in both V1 and V2, differing only in spatial scale, we predict that this pattern of above-threshold attentional activation of layer 6 but not 4 should hold in both areas. It is possible that only very attentionally demanding tasks, requiring discriminations at fine spatial resolution, will reveal such activity in V1. A similarity between attention and grouping that the model proposes is that V2 groupings should feed back into V1 through the same pathway as attentional signals. For example, widely spaced collinear inducers [like the flankers in the study by Polat *et al.* (Polat *et al.*, 1998)], should cause illusory contour activation in V2 layer 2/3, but not V1 layer 2/3, with feedback from this V2 grouping supraliminally activating V1 layer 6 but not 4, just like attention to empty space. The model also proposes explicit mechanisms by which attention and grouping can mutually interact: it is predicted that atten- tional signals should be able to pass via the modulatory layer 6→4 path into an already active layer 2/3 grouping, along which the attentional enhancement can then propagate. This is the mechanism that underlies the model's simulation of the experiment by Roelfsema *et al.* (see Fig. 2 above). The model predicts that attention should be able to propagate not only along real contours, such as the traced curves in the Roelfsema experiment, but also along illusory contours, as is simulated by Raizada and Grossberg (Raizada and Grossberg 2001, Fig. 5). Thus, if a version of the Roelfsema *et al.* experiment were to be conducted using curves made of dashed lines instead of unbroken contours, then the model would predict that attention should boost the firing of layer 2/3 cells whose receptive fields lie along the gaps in the traced curve, as well as those whose receptive fields lie on the solid sections. Additional predictions made by the model have been discussed elsewhere (Grossberg and Raizada, 2000; Raizada and Grossberg, 2001).

In summary, we believe that investigating the functional roles of the layers of cortex constitutes one of the most promising open frontiers in present-day neuroscience. Theoretical and computational analyses of the types of information processing that cortex is carrying out can help to guide us in trying to interpret its complex laminar circuitry. One example of a type of computation that appears to be common across many cortical areas is the lateral grouping of signals from neurons that have similar response properties. Another is the selective attentional enhancement of relevant stimuli, and the suppression of irrelevant stimuli. The model that we have presented here makes detailed structural and functional predictions concerning how these computations might be implemented in specific visual cortical circuits. Exploring how these and other computations are performed in the exquisite six-layered architecture of cortex promises to be a source of many rich and challenging opportunities for future research.

Notes

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