Texture Segregation By Visual Cortex: Perceptual Grouping, Attention, and Learning

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Boston University
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Rushi Bhatt1, Gail A. Carpenter2, and Stephen Grossberg3

Department of Cognitive and Neural Systems
And
Center for Adaptive Systems
Boston University
677 Beacon Street, Boston, MA 02215
Phone: 617 353 7858
Fax: 617 353 7755

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Correspondence should be addressed to:
Stephen Grossberg
Department of Cognitive and Neural Systems
Boston University, 677 Beacon St., Boston, MA 02215
Phone: (617) 353-7858
Fax: (617) 353-7755
Email: steve@bu.edu

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Abstract
A neural model is proposed of how laminar interactions in the visual cortex may learn and recognize object texture and form boundaries. The model brings together five interacting processes: region-based texture classification, contour-based boundary grouping, surface filling-in, spatial attention, and object attention. The model shows how form boundaries can determine regions in which surface filling-in occurs; how surface filling-in interacts with spatial attention to generate a form-fitting distribution of spatial attention, or attentional shroud; how the strongest shroud can inhibit weaker shrouds; and how the winning shroud regulates learning of texture categories, and thus the allocation of object attention. The model can discriminate abutted textures with blurred boundaries and is sensitive to texture boundary attributes like discontinuities in orientation and texture flow curvature as well as to relative orientations of texture elements. The model quantitatively fits a large set of human psychophysical data on orientation-based textures. Object boundary output of the model is compared to computer vision algorithms using a set of human segmented photographic images. The model classifies textures and suppresses noise using a multiple scale oriented filterbank and a distributed Adaptive Resonance Theory (dART) classifier. The matched signal between the bottom-up texture inputs and top-down learned texture categories is utilized by oriented competitive and cooperative grouping processes to generate texture boundaries that control surface filling-in and spatial attention. Top-down modulatory attentional feedback from boundary and surface representations to early filtering stages results in enhanced texture boundaries and more efficient learning of texture within attended surface regions. Surface-based attention also provides a self-supervising training signal for learning new textures. Importance of the surface-based attentional feedback in texture learning and classification is tested using a set of textured images from the Brodatz micro-texture album. Benchmark studies vary from 95.1% to 98.6% with attention, and from 90.6% to 93.2% without attention.
1 Introduction

Object recognition is a fundamental behavioral requirement for animals. Humans and other higher primates are remarkably capable of recognizing and discriminating between different objects in visual scenes using a variety of cues like global object form, local texture, brightness gradients, shading, disparity, and motion. Object recognition in response to an arbitrary scene is a computationally hard problem. Yet, the visual system rapidly and effortlessly performs this task with a very high degree of success and reliability.

How does the brain so effortlessly learn to recognize the global forms of objects at the same time that it learns their surface attributes like local textures? It is well known that sometimes objects can be recognized just from their local texture and that texture boundaries and global object form are not always needed or sufficient for recognition (Biederman, 1981; Gurnsey & Laundry, 1992; Renninger & Malik, 2004). On the other hand, object form, notably texture boundaries, are often an important cue for object recognition (Beck, 1982; Biederman & Ju, 1988; Elder & Zucker, 1998; Grossberg & Mingolla, 1985b; Nothdurft, 1985). This article develops a neural model, called the Distributed ARTEX (dARTEX) model (Figure 1), which can learn both global object form and local object texture by operating at different scales of processing. This model also clarifies how spatial and object attention can work together to facilitate object and texture learning and recognition tasks.

The dARTEX model is inspired by two parallel streams of modeling work. The first stream developed a 3D LAMINART model to explain and predict how the laminar circuits of visual cortex lead to visual percepts; e.g., Grossberg (2003), Grossberg & Howe (2003), Grossberg, Mingolla, & Ross (1997), Grossberg & Raizada (2000), Grossberg & Seitz (2003), Grossberg & Swaminathan (2004), Grossberg & Williamson (2001), Grossberg & Yazdanbakhsh (2005), Raizada & Grossberg (2001, 2003). The 3D LAMINART model provides a unified account of various perceptual and neurobiological data concerning cortical areas V1 to V4. In particular, the 3D LAMINART model predicts how processes of perceptual development and learning; bottom-up perceptual filtering; horizontal perceptual grouping, including boundary completion during the formation of illusory contours and the grouping of texture elements; compensation for variable illumination and surface filling-in; and top-down attention interact in a parsimonious and ingenious way within well-known laminar cortical circuits.

The second stream models how the inferotemporal and prefrontal cortices work together to achieve fast, stable, incremental learning of distributed visual recognition categories in response to complex and changing visual environments. The foundations of this latter modeling stream were laid in articles about Adaptive Resonance Theory, or ART, models of visual learning and recognition; e.g., Carpenter & Grossberg (1987, 1991), Carpenter, Grossberg, Markuzon, Reynolds, & Rosen (1992), Carpenter, Grossberg, & Reynolds (1991a), Carpenter, Grossberg, & Rosen (1991b), Grossberg (1976, 1978, 1980), and Grossberg & Williamson (1999). These foundational ART models used winner-take-all recognition categories. The main predicted properties of ART circuits have recently received support from neurophysiological and anatomical experiments, in addition to earlier supportive psychological data; see Grossberg (1995, 2003) and Raizada & Grossberg (2003) for reviews.

The ARTEX model of Grossberg & Williamson (1999) joined together visual preprocessing (multiple-scale bottom-up filtering, horizontal grouping, and surface filling-in) as a perceptual front end to an ART classifier to learn and categorize both Brodatz textures and natural textured scenes after they were processed by a synthetic aperture radar (SAR) sensor.

The present work is in the spirit of the Grossberg & Williamson (1999) study. It builds upon a more recent development of ART, called Distributed ART, or dART, which demonstrated how the useful properties of fast, stable, incremental learning and recognition can be realized in a system that can learn distributed, rather than winner-take-all, code representations (Carpenter, 1997, 2001; Carpenter, Milenova, & Noeske, 1998).

The resulting dARTEX model uses multiple-scale bottom-up filtering, horizontal grouping, and top-
down spatial and object attention, in addition to a dART classifier, in a laminar cortical circuit model. The dARTEX model is used to quantitatively simulate a large set of challenging human psychophysical data about Orientation-Based Texture Segmentation (OBTS) from the experiments by Ben-Shahar & Zucker (2004). Figure 2 shows some of the texture stimuli used in these experiments. Figure 3 describes the data and the dARTEX simulations of these data.

A complete, quantitative explanation of OBTS data is important because it illustrates important issues in perceptual differences due to variations in orientation gradients in the scene and differences in element configurations at texture boundaries. These configural effects in texture segmentation have long been observed, but a comprehensive, quantitative, and mechanistic explanation of the processes underlying the asymmetries in boundary perception due to texture element configuration and distribution of their orientation has been lacking in the literature (Beck, 1982; Ben-Shahar & Zucker, 2004; Nothdurft, 1985; Olson & Attneave, 1970; Wolfson & Landy, 1995).

In addition to explaining the OBTS data, dARTEX achieves favorable benchmarks compared to other texture classifiers in the computer vision literature (Greenspan, Goodman, Chellappa, & Anderson, 1994;
We show through computer simulations that the improved texture classification benchmark performance of dARTEX is due to top-down spatial attention and autonomous self-supervised learning of novel textures from the visual scene. As will be demonstrated in Section 2.11, these mechanisms in dARTEX reduce classification errors at texture boundaries by preventing mixing of features from different textures during classification. Prior texture classification approaches do not employ such attentional modulation to prevent the mixing, and therefore are most susceptible to classification errors at the interface of abutted textures.

A key new insight of the dARTEX model is to show how spatial attention leads to a surface-based attentional signal that can significantly enhance texture learning and recognition, including the regulation of this learning by object attention. Thus, the present work proposes how spatial and object attention may be coordinated in order to achieve efficient, indeed effortless, object learning and recognition. Related work by Fazl, Grossberg, & Mingolla (2005) shows how such a surface-based attentional signal, or attentional shroud (Tyler & Kontsevich, 1995), can be used to learn view-invariant object categories while the eye actively searches a scene and redirects visual attention to multiple locations in that scene. The present work shows how multiple scales of learning and recognition can be coordinated by such an attentional shroud to learn both object texture and form.

The rest of this article is organized as follows. The remainder of this section describes psychophysical and physiological data addressed by dARTEX. Section 2 introduces the dARTEX model and demonstrates its computational properties with the help of computer simulations. Section 2 also describes benchmark texture classification results using a set of images from the Brodatz (1966) album. Section 3 describes the orientation-based texture segmentation experiments of Ben-Shahar & Zucker (2004) and compares dARTEX simulations to the experimental data. Section 4 discusses related prior studies. Section 5 provides a discussion and conclusions. Mathematical specification of dARTEX is included in the Appendices.

1.1 Psychophysical and Physiological Data Explained by dARTEX. Computer simulations of dARTEX presented in this paper strive to explain how boundary-based texture segmentation processes and local surface classification processes may interact to achieve self-supervised surface feature learning and facilitate texture classification and object boundary localization. Experimental data addressed by dARTEX towards this end is described next.

Effortless, pre-attentive, texture boundary processing requires local feature detection, feature contrast detection, and long-range grouping (Beck, 1982; Bergen & Landy, 1991; Caelli, 1985; Grossberg & Mingolla, 1985b; Sutter, Beck, & Graham, 1989). Differences in texture luminance, color, orientation, density, size, element shape, relative placement, and the statistical distribution of the texture features have all been

![Figure 2 (on the next page): dARTEX boundary grouping outputs denoting texture boundaries in some interesting stimuli from the Ben-Shahar and Zucker (2004) experiments. In each panel, top figure is the input to dARTEX and the bottom figure is the boundary grouping activity in V2 layers 2/3 added over all three scales for 12 orientations. Length of each oriented line segment is proportional to the boundary activity in that orientation at that location. The perceptual saliencies in each case can be explained through grouping boundaries and top-down amplification of elements through boundary-based attention. Here, $\Delta k_T$ is the tangential curvature discontinuity at the horizontal boundary, $\Delta k_N$ is the normal curvature discontinuity, $\Delta \theta_b$ is the angular discontinuity at the boundary, and $\Delta \theta_w$ is the image orientation gradient magnitude. See text for a complete description of these stimuli. (a) $\Delta k_T = \max$ configuration, $\Delta \theta_w = 5^\circ$, and $\Delta \theta_b = 30^\circ$ (b) $\Delta k_N = \max$, $\Delta \theta_w = 5^\circ$ and $\Delta \theta_b = 30^\circ$ (c) $\Delta k_T = \Delta k_N$, $\Delta \theta_w = 5^\circ$ and $\Delta \theta_b = 90^\circ$ (d) $\Delta k_T = \max$, $\Delta \theta_w = 15^\circ$, $\Delta \theta_b = 90^\circ$ (e) $\Delta k_N = \max$, $\Delta \theta_w = 15^\circ$, $\Delta \theta_b = 90^\circ$ (f) $\Delta k_T = \Delta k_N$, $\Delta \theta_w = 15^\circ$, $\Delta \theta_b = 90^\circ$]
found to influence texture segmentation (Beck, 1982; Bergen & Julesz, 1983; Grossberg & Mingolla, 1985b; Julesz, 1986; Malik & Perona, 1990; Nothdurft, 1985; Wolfson & Landy, 1998). Perceptual effects of the various attributes of Orientation Defined Textures (ODTs), which are generally made of tilings of oriented bars, have long been investigated. Examples of such textures are shown in Figure 2. Perceived segregation strength of ODTs in general depends on both the magnitude of orientation discontinuity at the boundary as well as the image orientation gradient (Ben-Shahar & Zucker, 2004; Nothdurft, 1985, 1992; Olson & Attnave, 1970). An increase in image orientation gradient, or the amount of angular variation, decreases boundary salience, while an increase in angular discontinuity at the boundary increases boundary salience (Nothdurft, 1985). Nothdurft (1992) showed that the ratio of angular discontinuity at the texture boundary and the orientation gradient in the image is a good predictor of perceived boundary salience, with higher ratios resulting in more salient boundaries. Texture element contrast, density, and relative sizes have also been shown to influence segregation strength (Nothdurft, 2000a, , 2000b). Importance of element configuration at the boundaries in ODTs has also been recognized (Beck, 1982; Nothdurft, 1985, 1992; Olson & Attnave, 1970). All other texture parameters being equal, oriented bars that are more parallel to the texture boundary produce stronger segregation than when they are oblique to the boundaries (Nothdurft, 1985, 1992; Wolfson & Landy, 1995). Consider, for example, the orientation-based textures in Figure 2. An increase in orientation discontinuity at the boundary results in a corresponding increase in the boundary salience; texture boundaries in Figure 2c are easier to detect than those in Figure 2a. As noted earlier, element configuration at the boundary plays an important role in segmentation. For the same boundary discontinuity amounts and image orientation gradients, elements parallel to the boundaries cause stronger boundary percepts; compare Figures 2a and 2b. As the orientation gradient in the image increases, the detection task gets harder. For example, for the same boundary discontinuity amounts, texture boundaries in Figure 2f are harder to detect than those in Figure 2c. Also, while configurations with elements parallel to the boundary may still yield detectable boundaries (Figure 2f), the task gets much harder for other element configurations as the orientation gradients increase. For example, the boundaries in Figures 2d and 2e are harder to detect than those in Figure 2f, even though the three images have the same orientation gradient and boundary discontinuity magnitudes but differ in element configurations at the boundaries. For each of the images shown in Figure 2, the accompanying dARTEX boundary grouping simulations below them reproduce these subjective observations on boundary detection.

Using textures like those in Figure 2, Ben-Shahar & Zucker (2004) have systematically investigated how various types of orientation flow discontinuities influence perceived texture boundary salience. To the best of our knowledge, the Ben-Shahar & Zucker (2004) study is the most comprehensive in terms of the parametric range and the number of different configurations investigated. We therefore choose the Orientation-Based Texture Segmentation (OBTS) data from Ben-Shahar & Zucker (2004) as the main target dataset for dARTEX texture boundary salience simulations. The stimuli and the parametric manipulations in the Ben-Shahar & Zucker (2004) experiments are described in more detail in Section 3.1. The dARTEX

**Figure 3 (on the next page):** Complete simulation results of the Ben-Shahar & Zucker (2004) experiments. Each panel shows detection accuracy curves for a specific image orientation gradient magnitude $\Delta \theta_{within}$ as the boundary angular discontinuity amount $\Delta \theta_{between}$ increases from 5° to 90°. Points marked by boxes (blue curves) belong to $\Delta k_T = \text{max}$ configurations, those marked by circles (red curves) are $\Delta k_N = \text{max}$ configurations, and those by crosses (green curves) are $\Delta k_T = \Delta k_N$ configurations. Each of these configurations leads to a different configuration of texture bars. Average performance over all configurations is marked by triangles (black curves). For each panel, the top figure shows experimental data and the bottom panel shows dARTEX salience outputs. See Section 3 for a complete description.
between \( \Delta \theta \) within = 5°

between \( \Delta \theta \) within = 10°

between \( \Delta \theta \) within = 15°

between \( \Delta \theta \) within = 20°

between \( \Delta \theta \) within = 25°

between \( \Delta \theta \) within = 30°
data simulations of human psychophysical performance with these stimuli are discussed in Sections 3.3 and 3.4.

The sensitivity to element configurations at texture boundaries discussed earlier in this section is difficult to explain using only the FRF model of human texture perception that was introduced by Grossberg & Mingolla (1985b). The FRF model consists of two Filtering stages with an intermediate Rectifying threshold; see also Bergen & Landy (1991), Bovik, Clark, & Geisler (1990), Graham, Beck, & Sutter (1992), Grossberg (1987), and Sutter et al. (1989).

Wolfson & Landy (1995) used a version of the FRF model with extra weight applied to the oriented channel aligned with the texture boundary itself to explain a subset of the configurual effects mentioned above. The extra weight explained the increased salience of boundaries when elements are parallel to them compared to when elements are oblique to them. As Ben-Shahar & Zucker (2004, p.267) pointed out: “Unfortunately, such an explanation introduces a chicken-and-egg problem; the outcome (i.e., the orientation edge) must be given as an input to the computational process from which it is supposed to emerge (and after all, the goal of OBTS is to find these edges)”. Wolfson & Landy (1995) also recognized this shortcoming of their FRF approach, mentioning that the method of assigning extra weight was “not particularly compelling” (Wolfson & Landy, 1995, p. 2782). In their study, Ben-Shahar & Zucker (2004) went on to identify two intrinsic image parameters, named tangential and normal curvatures, and showed them to be intimately linked to the configural effects (see Section 4 of Ben-Shahar & Zucker, 2004) and Section 3 in this paper. Ben-Shahar & Zucker (2004) further argued that any data fit that simply uses extra weight for certain boundary configurations or certain orientation gradient values without any regard to the vector nature of the image orientation gradient does not account for all their observations. For example, each panel in Figure 3 pertains to a fixed image orientation gradient magnitude, denoted by $\Delta \theta_{\text{within}}$, and, for each trace, the tangential and normal curvatures change in a specific way. For certain image orientation gradient magnitudes ($\Delta \theta_{\text{within}} \leq 15^\circ$, see Figures 3a, 3b, and 3d), there is a crossover between the curves depicted by boxes and crosses (the blue and the green curves), which vanishes when $\Delta \theta_{\text{within}} = 20^\circ$; see Figure 3e. Ben-Shahar and Zucker further argued that selectively enhancing certain configurations (e.g., Wolfson & Landy, 1995) or image orientation gradients does not explain salience crossovers (i.e., Figures 3a, 3b, and 3d) that vanish simply by increasing the image orientation gradient (i.e., Figure 3e)

Nevertheless, a scheme that selectively enhances certain image features based on higher-level computations is at least part of the explanation, and forms a foundation for further investigation. In particular, sensitivity in OBTS to the angular discontinuity magnitude at the boundary is easier to explain using a center-surround competition, wherein higher angular discontinuity results in larger feature contrast and therefore stronger boundaries. However, the finer distinctions due to element configuration at the boundary, like those in Figure 2, cannot be explained simply by the contrast in bottom-up oriented filter activities. In their article that introduced the FRF concept, Grossberg & Mingolla (1985b) showed how FRF processes form part of a larger theory of perceptual grouping that may address the configural effects in OBTS. In particular, Cruthirds, Gove, Grossberg, & Mingolla (1991) analyzed bipartite texture discrimination data of Beck, Prazdny, & Rosenfeld (1983) and used FRF combined with grouping to simulate data that FRF could not fully explain. Using dARTEX simulations, it will be shown in Section 3 that boundary grouping, when combined with object-based attentional feedback that enhances grouped boundaries, and spatial attentional feedback that enhances features within surfaces that are surrounded by such boundaries, together explain the asymmetry in boundary saliencies due to element configuration and indeed the complete set of OBTS experimental data. See Section 3.2 for a complete description of the OBTS salience measure used for dARTEX data fit that relies on such attentional signals. By providing a mechanistic and quantitative fit to the OBTS data, the dARTEX model builds upon the approach taken by Wolfson & Landy (1995).

In addition to object boundary detection, region-based and local classification processes also play an important role in texture processing (Bovik et al., 1990; Caelli, 1985, 1988; Greenspan et al., 1994; Grossberg & Williamson, 1999; Jain & Farrokhnia, 1991). Human texture discrimination performance remains robust
even when the boundary between juxtaposed textures is blurred, or when there is empty space between the
two textures to be discriminated (Gurnsey & Laundry, 1992; Wolfson & Landy, 1998). An abrupt texture
gradient, therefore, is not a necessary condition for the discrimination of certain textures. These facts also
suggest that there is a spatially localized classification process involved in texture discrimination when the
textures differ in their overall feature patterns (Grossberg & Williamson, 1999; Gurnsey & Laundry, 1992).
Using textures comprising oriented line segments, Wolfson & Landy (1998) observed that better discrimina-
tion performance is achieved when two textures with large differences in their mean orientations are abutted
and have a sharp transition compared to being spatially separated by blank space. When the same type of
textures differ in standard deviation of the orientation of line segments but have the same mean orientation,
their discriminability remains unaffected by spatial separation or abutment. The importance of abutment
when textures differ in mean orientation but not when they differ in the standard deviation with the same
mean furthers the case for local classification-based surface processing in addition to the boundary-based
processing.

Based on the data described above, one may conclude that boundary-based processing helps to detect
sharp transitions in feature distribution, while classification processes are sensitive to local activity patterns
of oriented filters (Grossberg & Williamson, 1999; Gurnsey & Laundry, 1992; Julesz, 1986; Rao & Lohse,

Another important set of data that has guided the development of dARTEX demonstrates contextual
modulation of visual cortical cells whose receptive fields lie on or inside figure boundaries. For exam-
ple, the relative orientation of texture elements outside a V1 cell’s receptive field can suppress or enhance
its firing rate (Kapadia, Ito, Gilbert, & Westheimer, 1995; Knierim & van Essen, 1992; Sillito, Grieve,
Jones, Cudeiro, & Davis, 1995; Zipser, Lamme, & Schiller, 1996). Some oriented cells in V1 also show
sensitivity to texture boundaries in their later responses, at around 80-100 ms after stimulus onset (Lee,
Mumford, Romero, & Lamme, 1998; Nothdurft, Gallant, & van Essen, 2000). For example, the later re-
sponses of V1 cells with vertical preferred orientation are enhanced due to a vertical figure boundary even
when the figure and ground are made of mutually perpendicular obliquely oriented texture features (Lee
et al., 1998, also see Figure 4 for a dARTEX simulation). Such modulation due to the presence of tex-
ture boundaries has been implicated as a possible mechanism of figure-ground segregation (Lee et al., 1998;
Roelfsema, Lamme, Spekreijse, & Bosch, 2002). These contextual modulations in activity occurring around
80-100ms after stimulus presentation have been linked to top-down modulatory influences (Hupé, James,
Payne, Lomber, Girard, & Bullier, 1998; Lamme, Supér, & Spekreijse, 1998; Roelfsema et al., 2002). A
combination of cooperative figure boundary grouping and boundary-based modulatory corticogeniculate
feedback in dARTEX helps explain these modulations of V1 activities at texture-defined figure boundaries.
In dARTEX, boundary-based attention derived from the grouping stages acts through modulatory cortico-
genulate feedback (Gove, Grossberg, & Mingolla, 1995) and enhances LGN activities at figure boundaries
while suppressing their surround. Figure 1 shows this connection from boundary grouping stages in V2 to
the LGN via V1. The enhancement of activity of the V1 cells at figure boundaries due to modulation of the
LGN via this pathway is consistent with observations by Lee et al. (1998). While modulatory corticocortical
feedback from V2 to V1 may also enhance activities of oriented V1 cells at grouped image locations (Bul-
lier, Hupé, James, & Girard, 1996; Grossberg, 2003), corticogeniculate feedback is the principal connection
in dARTEX that links to the observations by Lee et al. (1998).

Primary visual cortical cell responses are also enhanced when their receptive fields lie in the interior of a
textured figure (Lamme, 1995; Zipser et al., 1996). One mechanism for accomplishing this type of property
is depicted in Figure 1, where the boundary-gated surface filling-in within cortical area V2 and volitional
surface attention mechanisms combine to result in surface-based top-down attentional feedback which gates
V1 simple cell responses.
2 The dARTEX Model

Operation of the dARTEX model can be described in two phases of processing. The initial processing phase involves fast feed-forward activation of most of the dARTEX stages, giving rise to boundary and surface attention. In the second phase of processing, spatial attention facilitates dART learning of texture features by selecting surface regions with similar texture features, and thereby enhances the accuracy of texture classification.

In what follows, dARTEX operations are illustrated using the input image in Figure 4a. Additional computational characteristics of dARTEX will be discussed using other simulations. In particular, simulations of the Orientation-Based Texture Segmentation (OBTS) experiments (Ben-Shahar & Zucker, 2004) will be discussed in Section 3.

Mathematical equations of dARTEX are provided in the Appendix. In order to facilitate cross-referencing, the Appendix equation number pertinent to the discussion will be provided in parentheses. Each dARTEX stage in the model diagram of Figure 1 is also labeled with the corresponding equation variable in the Appendix.

2.1 Center-Surround Field, LGN. Retinal and Lateral Geniculate Nucleus (LGN) processing are lumped together for simplicity. As seen in Figure 1, the model LGN receives bottom-up retinal input image as well as a top-down modulatory corticogeniculate boundary-based attentional feedback signal. LGN output signals input to simple cells in V1 layers 6 and 4 as well as to a surface filling-in process in V4.

The LGN contains ON cells and OFF cells. ON cells obey membrane, or shunting, equations and interact via on-center, off-surround interactions (Equation (A4)). This competition discounts the illuminant in the scene and normalizes local image contrasts. The center-surround operations are carried out at three successively increasing, equally spaced scales of spatial interaction. Cells in the complementary OFF channel interact via an off-center, on-surround network. Both ON and OFF channels provide bottom-up inputs to the simple cells in V1. See Grossberg, Mingolla, & Williamson (1995) for an example of how such prepro-

Figure 4 (on the next page): dARTEX simulations on an example input image. For panels g-i, darker pixels denote higher activity. Insets in panels b, c, e, and f are magnified versions of the grayed regions. (a) Input. (b) Output of the two competitive stages of V2, without boundary-based attention modulating the LGN activities. (c) Bipole cell outputs without boundary-based attention. Boundaries of the square figure are very weak for the appropriate orientation. (d) LGN stage activities with boundary-based attention amplifying boundary elements through corticogeniculate feedback. (e) V2 competitive stage outputs with boundary-based attention. The boundaries are further amplified compared to those in panel b and horizontal and vertical orientations show improved activity at the figure boundaries. (f) Bipole stage robustly group the vertical and horizontal square figure boundaries. (g) Featural signal to the surface filling-in domain at equilibrium. This signal is a combination of bottom-up arriving LGN activity and top-down volitionally selected surface attention. (h) Surface filling-in activity added over all scales at equilibrium. Features in panel g are contained by boundaries in panel f during filling-in. (i) Attentional shroud at the surface-attention level. The dark spot in the middle of the shroud is the top-down volitional spatial attention signal. Long-range spatial competition inhibits all surface activity except in the attended surface. This signal gates simple cell activities in V1 during feature learning and classification. (j) Featural signal at equilibrium after volitional attention shifts to the background. (k) Corresponding featural filling-in activity at equilibrium. (l) Attentional shroud at the surface-attention level. The dark spot in the background region is the volitional spatial attentional signal.
cessing helps to process complex imagery. See Roska, Molnar, & Werblin (2006) for consistent data about ON and OFF retinal processing.

As seen in Figure 1, a boundary-based corticogeniculate attentional feedback (Section 2.6) acts on LGN cells (Equation (A4)). This feedback is derived from boundary grouping cells in V2 layer 2/3. It selectively enhances LGN activities at texture boundaries through an on-center kernel while suppressing features in the boundary neighborhoods through an off-surround kernel. This boundary-based attentional signal enhances LGN activities at the texture boundaries; see Figure 4d.

2.2 Oriented Simple Cells, V1 Layers 6 and 4. Two sets of oriented simple cells, one each in V1 layers 6 and 4, serve as oriented filters of the image. The simple cells sample direct bottom-up activity from the LGN ON and OFF channels; see Figure 1 for block-level connectivity. In each set, a total of 24 orientations are used for each of the three LGN center-surround scales (Equation (A6)).

Layer 6 simple cells are identical to the layer 4 simple cells in terms of their bottom-up receptive fields. However, layer 6 simple cells are also gain-modulated through a form-fitting locus of top-down spatial attention; see Equation (A10). Spatial attention in dARTEX is hypothesized to act at V1 layer 6 through a corticocortical feedback pathway originating at PPC (Felleman & van Essen, 1991). While this may be a multi-stage pathway in vivo, dARTEX instantiates this as a direct pathway. Formation, volitional selection, and maintenance of spatial attention in dARTEX is described in Section 2.8. Spatial attention in dARTEX serves two purposes: First, much in the same way as the boundary-based attentional modulation of the model LGN, spatial attention maintains layer 6 simple cell activities at attended positions while suppressing activity at unattended positions around the locus of attention; see Equation (A10). The suppression of unattended activity prevents mixing of surface features across texture boundaries, resulting in improved texture learning and classification performance; see Section 2.11. Second, it acts to modulate texture category learning, such that texture features within the boundary of the attended surface may be learned as part of the same texture category. A parallel line of modeling by Fazl et al. (2005) shows how spatial attention binds multiple views of visual objects into view-invariant object categories.

In dARTEX, dART texture category cells are activated bottom-up by V1 layer 6 simple cells; see Figure 1. This bottom-up texture category activation plays two roles: First, it performs a pixel-by-pixel classification of image texture. Second, dART categories can be activated as expectations via this layer 6 to 4 network (Callaway, 1998; Grossberg & Raizada, 2000). Layer 4 simple cell activity matched with this feature expectation (Equation (A13)) constitutes bottom-up input to the complex cell filters in layers 2/3 of V1.

In the initial, feedforward, processing phase of dARTEX, spatial attention is inactive, and layer 6 simple cell activity is identical to layer 4 simple cell activity; see Equation (A12). Learning at this time converts the matched layer 4 simple cell activity into a noise-suppressed version of bottom-up simple cell activity; see Equation (A13). Image noise reduction obtained by this feature match is discussed in Section 2.9. Further activation of dARTEX hierarchy gives rise to pre-attentively defined figural boundaries and surfaces. Interaction of these surfaces and spatially localized top-down volitional selection gives rise to form-fitting spatial attention; see Sections 2.7 and 2.8. By acting on layer 6 simple cells as described earlier, spatial attention influences dART classification and learning. This dARTEX property is also discussed in Section 2.9. The dARTEX activation phases of feedforward activation, boundary- and surface-based attentional modulation, and texture learning are summarized in Section 2.10.

2.3 Complex Cells, V1 Layer 2/3. Complex cell filters in V1 layer 2/3 combine rectified matched layer 4 simple cell outputs (Equation (A10)) of the same scale but opposite contrast polarities (Equation (A14)), resulting in 12 orientations of complex cells for each of the three spatial scales (Ferster & Miller, 2000; Hubel & Wiesel, 1959, 1968). Complex cells act as polarity-of-contrast insensitive, oriented, multi-scale filters.

2.4 Spatial and Orientational Competition, V2 Layers 6 and 4. Feature contrast enhancement is accomplished by two stages of competitive interactions (Equations (A15) and (A18)) in layers 6 and 4 of V2.
As seen in Figure 1, the first competitive stage in V2 constitutes a spatial center-surround competition between similarly oriented complex cells (Equation (A16)). This stage picks out discontinuities in the spatial activity distribution of similarly oriented complex cells, signaling a local texture feature contrast and realizes an end stop operation (Hubel & Wiesel, 1977).

The second, orientational, competition stage in V2 is driven by the outcome of the spatial competition and acts at a smaller spatial scale wherein mutually orthogonal orientations inhibit each other the most (Equation (A19)). This competition reduces activity at image locations with ambiguity in feature orientation and thus helps reduce unoriented noise. The orientational competition stage also realizes an end-cut operation mechanism (Grossberg & Mingolla, 1985b). End cutting produces hyper-acute responses at the endings of oriented bars through disinhibition at bar endings of orientations that are perpendicular to those that the bar directly activates. This end-cut mechanism helps to enhance activities at bar endings and to thereby facilitate illusory contour grouping between multiple bars (Gove et al., 1995; Grossberg & Mingolla, 1985b; Ross, Grossberg, & Mingolla, 2000).

The two competitive stages induce strong featural activities at texture boundaries while suppressing uniformly oriented texture elements within figure interiors and the background; see Figure 4b.

These processing stages were initially proposed as part of the Boundary Contour System (BCS) of Grossberg & Mingolla (1985b) and have since become a standard component in many texture segmentation algorithms and models of human texture processing. In particular, the processing stages of oriented filtering, pointwise rectification, and spatial competition comprise the Filter-Rectification-Filter (FRF) approach to texture segregation (Bergen & Landy, 1991; Bovik et al., 1990; Graham et al., 1992; Greenspan et al., 1994; Jain & Farrokhnia, 1991; Sutter et al., 1989).

### 2.5 Bipole Grouping Cells, V2 Layer 2/3.

The bipole cells in layers 2/3 of V2 (Equation (A21)) carry out perceptual grouping by forming and, where necessary, completing oriented figural boundaries in responses to inputs from the competitive stages of V2. As seen in Figure 1, the bipole cells receive direct bottom-up inputs from the orientational competition stage. Orientationally pooled boundaries input to the surface filling-in stage in V4 and also realize boundary-based attentional feedback to the LGN; see Figure 1.

Interactions between the pyramidal (bipole) cells in layer 2/3 of V2 (Equation (A21)) realize the bipole grouping stage, whereby cells that are (approximately) collinear and coaxial with respect to one another across space can excite each other via long-range horizontal connections. These long-range horizontal connections also activate interneurons that inhibit each other and nearby pyramidal cells via short-range disynaptic inhibition (Equation (A29)). This balance of excitation and inhibition at target cells helps to implement the bipole property, whereby the cell can fire either by strong bottom-up excitatory input from the competitive stages, or when above-threshold excitatory inputs arrive from both its long-range horizontal flanks. This latter trait is described next.

In the absence of strong bottom-up input to the bipole cell, excitation from only one of the horizontal flanks creates a case of “one-against-one” wherein the cell gets commensurate amounts of excitation from the long-range excitatory connections and inhibition from the shared pool of inhibitory interneurons. The bipole cell is thereby not excited above threshold. On the other hand, when two collinearly aligned inducing stimuli are present, one on each flank, a boundary grouping can form even without direct bottom-up input. This is because the inhibitory interneurons, apart from inhibiting the bipole cell, also inhibit each other, thus normalizing the total amount of inhibition emanating from the interneuron pool. This summating excitation and normalizing inhibition create a case of “two-against-one” and the target cell is excited above threshold. In addition to this competitive interaction via the shared pool of inhibitory interneurons, bipole cells that are sensitive to different orientations also compete (Equation (A28)). This orientational competition sharpens bipole responses for well-grouped orientations while reducing ambiguity in orientation at each image location.

The bipole mechanism described above is also sensitive to the degree of collinearity and relative dis-
stances of features; see Equation (A23). This sensitivity of the bipole cells is important in explaining the OBTS data as described in Section 3. The complete bipole stage is mathematically described in Equations (A21) through (A29).

The bipole grouping mechanism was first proposed by Grossberg (1984) and by Grossberg & Mingolla (1985a, 1985b). It has since been used to explain a variety of perceptual grouping percepts (e.g., Gove et al., 1995; Grossberg & Howe, 2003; Grossberg & Swaminathan, 2004; Ross et al., 2000). Cells with long-range monosynaptic, recurrent, excitatory connections and local disynaptic inhibitory connectivity have been reported in the visual cortex (Hirsch & Gilbert, 1991; McGuire, Gilbert, Rivlin, & Wiesel, 1991). The bipole property has also been observed in physiological recordings from cells in macaque area V2 (von der Heydt & Peterhans, 1989; von der Heydt, Peterhans, & Baumgartner, 1984). Psychophysical evidence of long-range perceptual grouping that obey the bipole property has been observed by several researchers (Field, Hayes, & Hess, 1993; Kellman, 2003; Kellman & Shipley, 1991). Long-range statistical correlations in co-aligned orientations have been observed in natural scenes, which provides an ecological stimulus for such long-range grouping (Sigman, Cecchi, Gilbert, & Magnasco, 2001).

2.6 Boundary-Based Attention, From V2 to LGN. For many feature configurations, contrast may not exist in the orientation of the form boundary itself. The image in Figure 4a is such an example. Although perceived emergent square boundaries in Figure 4a are vertical and horizontal, there is neither luminance nor horizontal and vertical orientation contrast at the boundaries to explicitly generate these boundaries. The end-cut mechanism realized by the two competitive stages in Section 2.4 disinhibits horizontal and vertical orientations at the ends of the oblique texture bars at the form boundaries; see Figure 4b. The long-range bipole grouping of these vertical and horizontal orientations along the figure boundaries result in figure boundaries in the appropriate orientations and locations. However, the end-cut mechanism and long-range bipole grouping only realize weak emergent square figure boundaries, and the strong oblique orientation contrast still overshadows the vertical and horizontal orientations; see Figure 4c.

Attentional amplification of features using grouped boundary activities helps generate strong vertical and horizontal boundaries in this case. As seen in Figure 1, boundary-based attention is derived by pooling bipole cell activities in V2 over all orientations and scales (Equation (A30)). This boundary-based attention signal modulates the LGN via V1 (Callaway, 1998; Grossberg, 1976; Guillery, 1967; Murphy & Sillito, 1987; Przybyszewski, Gaska, Foote, & Pollen, 2000; Sillito & Jones, 2002; Sillito, Jones, Gerstein, & West, 1994). The resultant increase in feature activity at the form boundaries is detected by the spatial competitive stage in all orientation channels, including the vertical and horizontal channels, as seen in Figure 4e. The bipole cells, which receive competitive stage activities as input, now robustly group and amplify the contrast signals along the emergent figure boundaries, as seen in Figure 4f, thus correctly signaling strong emergent figure boundaries.

Note that the corticogeniculate feedback in dARTEX is modulatory, and therefore amplifies grouped features without creating new image features (Gove et al., 1995). Such a modulatory feedback process was predicted in the context of the Adaptive Resonance Theory, or ART, by Grossberg (1976, 1980). It has been modeled to explain various perceptual effects (Gove et al., 1995; Grossberg & Grunewald, 2002; Grossberg & Raizada, 2000; Raizada & Grossberg, 2001), including those of Sillito et al. (1994), which ART predicted (Grossberg, 1976).

2.7 Surface Filling-In Domain, V4. As described in Sections 2.1 through 2.6, dARTEX computations pre-attentively and automatically define emergent figural boundaries using discontinuities in local feature distributions. A surface filling-in process in V4 (among other cortical areas, see Cao & Grossberg, 2005; Fang & Grossberg, 2005; Grossberg, 1994) is controlled by these pre-attentive boundaries.

Figure boundaries signaled by the bipole cells in V2 layers 2/3 gate the filling-in of surface feature signal arriving from the LGN (Cohen & Grossberg, 1984; Grossberg & Mingolla, 1985a; Grossberg & Todorović, 1988); see Figure 1 and Equation (A31). Feature signal inputs to the filling-in domain arrive from the LGN. The boundary-gated spread of these surface features tends to generate uniform filled-in activity levels
within each boundary compartment. Filled-in activities can be very different in different compartments of the scene. Figure 4 shows examples of this filling-in process: Figure boundaries are shown in Figure 4f, surface featural inputs are shown in Figures 4g and 4j, and the corresponding filled-in activities are shown in Figures 4h and 4k, respectively.

Surface filling-in at each spatial scale contributes in a different way toward the combined filled-in activity. At the smallest scale, boundaries enclosing individual texture bars contain the bar feature. At larger scales, surface feature diffusion is contained principally by object form boundaries, leading to uniformly filled-in activity within each surface. Surface filling-in signal combined over all spatial scales therefore describes individual bars as well as object form; see Figures 4h and 4k.

2.8 Spatial Attention, PPC. The surface filling-in domain in V4 and spatial attention stage in the Posterior Parietal Cortex, or PPC (Colby & Goldberg, 1999; Deubel & Schneider, 1996), are bidirectionally linked; see Figure 1. The spatial attention stage (Equation (A33)) of dARTEX receives filled-in surface activities from the filling-in domain of V4, described above, and projects back to the filling-in domain. In the spatial attention stage, pre-attentively filled-in surfaces in the scene bid for attention. Depending on the task demands, top-down localized volitional spatial attention may also select a location of interest by locally enhancing its activity (see term $I_{pq}$ in Equation (A33)). Due to the back projection from spatial attention to surface filling-in (see Equation (A31), activity of the volitionally selected surface gets enhanced (Reynolds & Desimone, 2003; Reynolds, Pasternak, & Desimone, 2000; Tse, 2005) through boundary gated spread of the volitional enhancement signal. Enhanced filled-in surface activity feeds forward to spatial attention stage, further enhancing the entire region fitting the attended surface form (cf., Cavanagh, Labianca, & Thornton, 2001; Pylyshyn, 1989; Tyler & Kontsevich, 1995). At the same time, other regions at the surface attention level are suppressed by this attended, enhanced, locus of spatial attention through long-range spatial competition (Carpenter & Grossberg, 1991; Desimone, 1998; Grossberg, 1994; Reynolds, Chelazzi, & Desimone, 1999).

Simulations in Figure 4 illustrate this interaction between the surface filling-in domain and the spatial attention stage. Figure 4g shows the total input to filling-in domain at equilibrium, which combines bottom-up LGN input (Equation (A4)) and top-down spatial attention input; also see Equation (A31). The bipole activities, depicted in Figure 4f, act as boundaries that gate the filling-in process. Boundary-gated filling-in leads to the square central figure surface shown in Figure 4h. Furthermore, the spatial attention stage shows strong activity at the winning surface and no activity elsewhere in the scene; see Figure 4i. Also note the dark spot close to the middle of the square central surface in Figures 4g and 4i, which is the top-down volitional attention signal (Equation (A33)) that biases the competition in favor of the attended surface.

Figures 4j, 4k, and 4l show how a shift in the volitional signal triggers a shift of form-fitting spatial attention to the newly selected surface. In the surface filling-in domain, boundary-gated diffusion of the shifted focal volitional attention increases filled-in activity in the figure background. Through long-range spatial competition, activity in the previously attended form is eliminated and the surviving spatial attentional signal fits the entire background. Spatially localized volitional attention thus determines which form-fitting locus constitutes the spatial attention signal. In the absence of a volitional focal attention biasing the competition for attention, a number of factors, including surface size, boundary strength, and feature intensity automatically generate a winning form-fitting spatial attention.

Surface filling-in at the different spatial scales responds differently to the localized volitional attentional enhancement. While at the larger spatial scales the filled-in signal of the entire attended surface is enhanced, at the smallest spatial scale, the focal attentional enhancement is trapped by the boundaries of the individual bar into which it falls, increasing its filled-in activity compared to other bars; note the darker bars at the focus of attention in Figures 4h and 4k.

A number of investigators have reported that spatial attention can mold itself to an object’s shape. Our simulations illustrate how this can happen through feedback between surface filling-in and spatial attention processes. One such concept is called an attentional shroud (Tyler & Kontsevich, 1995). Our simulation
of how an attentional shroud forms adapts the process described in Fazl et al. (2005), who show how such shrouds can be used to regulate the learning of 3D invariant object categories from multiple object views. Other investigators have reported data showing how the allocation of spatial attention can depend upon the spatial location of objects (Connor, Preddie, Gallant, & van Essen, 1997; Connor, Gallant, Preddie, & van Essen, 1996; Johnson & Yantis, 1995; Posner, 1980; Pylyshyn & Storm, 1988; Sagi & Julesz, 1986; Yeshurun & Carrasco, 2000), specific stimulus features (Cavanagh, 1992; Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1990; Wolfe, Cave, & Franzel, 1989), and the nature, salience, and importance of the visual object itself (Blaser, Pylyshyn, & Holcombe, 2000; Duncan, 1984; Mitchell, Stoner, Fallah, & Reynolds, 2003; O’Craven, Downing, & Kanwisher, 1999; Treisman & Paterson, 1984). Both Fazl et al. (2005) and the present work illustrate how spatial attention can regulate category learning and, during that learning process, the allocation of object attention.

2.9 dART-Based Texture Learning, Classification, and Top-Down Attentive Matching. The dART network in the model is driven by spatially pooled V1 layer 6 simple cell activities; see Equation (A34) and Figure 1. The dART network learns to assign a texture category to each image pixel using these simple cell activity patterns. Carpenter (1997) introduced the dART model to explain how fast, incremental, and stable learning of categories could be achieved while allowing for arbitrarily distributed category activation. Such category representation was shown to have desirable category generalization and compression characteristics (Carpenter et al., 1998).

The spatial distribution of feature activity in natural images is typically variable, even for a visually homogeneous texture. During bottom-up texture category learning by the dART network, a top-down expectation (Equation (A35)) is also learned and subsequently matched against layer 4 simple cells; see Equation (A13). The match operation in layer 4 of V1 is an interface between pre-attentive texture processing and attentive local texture classification (Grossberg, 1999a, 2003) that acts via the layer 6 to 4 modulatory network (Callaway, 1998; Grossberg & Raizada, 2000; Salin & Bullier, 1995; Wiser & Callaway, 1996). This top-down matching process suppresses noise in simple cell activities as follows.

According to the distributed ART match rule used in dARTEX (Carpenter, 1997, 2001; Carpenter et al., 1998), the matched feature is the smaller of the layer 4 simple cell activity and the top-down feature expectation (Equation (A13)). This match operation suppresses noisy pixels that deviate significantly from prototypical texture features, leading to feature activity due to texture features rather than noisy deviations of them. By eliminating such noise, texture category matching facilitates completion of a boundary grouping around the texture-induced form, and thus the formation of a form-fitting attentional shroud. The shroud, in turn, additionally facilitates texture category learning by eliminating texture exemplars that belong to different forms; cf., Equation (A10).

Figure 5a demonstrates the utility of feature match using a noisy textured image. With a high variability in bar orientation, the competitive stages of V2 have a hard time in detecting feature discontinuity (Figure 5b). Using the matched simple cells, on the other hand, the competitive stages can suppress the interior features and pick out the boundaries successfully (Figure 5c). The bipole grouping stage can now signal the figure boundaries correctly (Figure 5d).

Figure 1 shows the top-down spatial attentional shroud pathway that acts as a modulatory gate for inputs to the dART network in V1 layer 6. During dART learning, the attended form remains active through the attentional shroud, via a surface-(spatial attention) resonance (Grossberg, 2003) which enables learning of attended surface features. The dART learning algorithm is described in Section B1. During dART learning, input feature vectors defined in Equation (A34) at attended image pixels are associated with a class name, or label. This class label may be externally supplied, or automatically generated based on task context. Benchmark simulations in Section 2.11 generate class labels using image presentation sequence number.

2.10 Summary of dARTEX operation modes. dARTEX bottom-up activation, emergence of the attentional shroud, and interaction of this attentional shroud with a dART feature match can be described by following modes of operation (cf. Grossberg, 1999b): In the initial bottom-up activation mode, the atten-
Figure 5: (a) Input image of oriented bar texture corrupted by Gaussian orientational noise. (b) Without a trained dART network, the competitive stages in V2 fail to produce clean figure boundaries. (c) Competitive stage outputs with a trained dART network rejecting image noise. The dART network was trained on noise-free oriented bar textures of four different orientations. (d) Using inputs in (c), bipole cells can now group features at the boundaries, signaling figure boundaries in the appropriate location and orientation. Local texture learning and surface attention are instrumental to noise rejection and improved classification. (e) An example input image from the Brodatz texture benchmark set. (f) Texture labels assigned by the ART network for each image pixel after applying top-down surface attention that prevents mixing of image features at the boundaries. True texture figure boundary is shown in white. Texture classification accuracy is 96.3% correct for this image. See Table 1 for complete statistics. (g) Average classification improvement due to surface attention. For the 40 images tested, darkness of the pixel denotes the number of times a correct classification was made after surface attention given a misclassification occurred without attention. (h) In same color-scale as (h), the count of misclassifications with surface attention given a given a correct classification before surface attention. Worsening of classification due to surface attention is minimal.
tional shroud is not yet active. The layer 4 match activity in this case is the noise-suppressed simple cell activity over the whole scene as described in Sections 2.2 and 2.9. Bottom-up activation of the rest of the dARTEX hierarchy through these matched simple cells gives rise to a form-fitting spatial attentional shroud; see Section 2.8. Activation of the spatial attentional shroud initiates attentive texture classification mode. In this mode, spatial attention suppresses layer 6 simple cell activity at unattended positions surrounding the attended form. This elimination of dART input from the surround prevents feature mixing across texture boundaries during the classification and improves model performance. In the final mode of dARTEX operation, the continued activation of the attentional shroud results in a surface-(spatial attention) resonance taking hold in which dART inputs remain active for long enough to be learned as the same texture; see Section 2.9. In the supervised learning mode utilized in dARTEX, a texture class label is also supplied at attended spatial locations during this resonance.

A large mismatch between bottom-up layer 4 feature and its top-down expectation may suppress layer 4 match activity at such positions. If the mismatch occurs over a sufficiently large spatial region after a shroud has formed, it may affect the shroud, triggering the activation of another shroud. Also, volitional top-down surface attention signal in the absence of bottom-up inputs may sensitize, or subliminally activate dART categories, but cannot create activity in layer 4. However, such a top-down priming signal may prepare a category cell to react more quickly and vigorously to subsequent bottom-up input that matches the top-down prime, resulting in rapid recognition of the primed feature. These aspects of spatial attentional reset and top-down priming are not investigated in the current model, but see Carpenter & Grossberg (1987) and Grossberg (1980, 1999b, 2003) for further discussion in the context of ART.

2.11 Texture Classification Benchmark Simulations. A benchmark image dataset derived from the Brodatz (1966) album helps elucidate the importance of top-down surface attention in texture learning and classification. The benchmark comparisons show that detrimental effects on texture learning and classification due to feature mixing at texture boundaries can be circumvented by top-down surface-based attentional shrouds. Top-down spatial attention also acts as a supervising signal, delineating textured regions that can be learned as part of the same texture category.

Figure 5e shows an example image from the benchmark dataset. Each such image in the dataset consists of a square textured figure on a textured background. Ten different texture materials were used from the Brodatz (1966) album for generating the dataset. The Brodatz images chosen are Grass, Herringbone Weave, Wool, French Canvas, Paper, Wood, Cotton Canvas, Oriental Cloth, Jeans, and Raffia. Grossberg & Williamson (1999) used this 10-texture library for evaluating their ARTEX model. To provide a quantitative estimate of the role of spatial attention in the current model, classification rate of dARTEX on single texture images was matched to that of ARTEX. The effect of spatial attention was then quantified by training and testing with or without attention on images with either two textures, e.g., shown in Figure 5e, or on single texture images. Classification results for all combinations of training and testing with or without attention, and on single-texture or two-texture images is summarized in Table 1. A study with nine images was also undertaken and summarized in Table 1, both to illustrate model robustness and to facilitate its comparison with other studies that used nine textures. The dataset generation and benchmark procedure is described next.

For training, a sequence of 40 images was generated, with each of the ten textures appearing four times in succession as the central square figure with another texture from the remaining nine textures for the background. The dART network was initially untrained. The image sequence was presented to dARTEX in blocks of four images. The volitional attentional signal $I_{ij}$ in Equation (A33) was a 3-by-3 pixel spot of activity located at a randomly chosen position in the central square figure. When this signal leads to a surface-(spatial attention) resonance, a form-fitting spatial attentional shroud emerges. The shroud determines the pixels to be associated with the supplied class label for each image presentation. A total of 1300 pixels, being 2% of the available training data, were randomly selected from those falling within the surface attention in the block of presentations. In order to compare classification performance with other super-
vised algorithms, the block sequence number was used as a class label for supervised training. Spatially pooled simple cell activities at image pixels selected through the above procedure and their assigned class labels constituted the dART training dataset (Equation (A34)). The dART training algorithm is described in Section B1. All dART network parameters were optimized using this training dataset by 10-fold cross-validation and five training epochs. Cross-validation error did not decrease with more than 1300 training samples per class.

A second dataset was generated by presenting each of the ten textures by itself as the input image, and using feature vectors from 1300 randomly selected pixels along with their true texture names as class labels. This dataset gave an estimate of the best achievable classification performance.

To investigate the role of surface attention for preventing feature mixing at the boundaries, a third dataset was constructed using the same 40 image set used for the first dataset. For this dataset, surface attention was prevented from modulating the layer 6 simple cells (Equation (A10)). The lack of surface attention resulted in mixing of features at texture boundaries, deteriorating the quality of training samples. The training set was generated by randomly selecting 325 image pixels from the central square figure of each image, with true texture names of the square figure as class labels. With four presentations of each texture, this amounted to 1300 samples per class, the same as for other datasets. When compared to classification performance on the first dataset, this dataset gave an estimate of classification error due to feature mixing at the boundaries during training.

Test classification accuracy was estimated using two datasets. The first dataset was generated with each of the ten textures presented by itself as the input image. The second dataset used every possible figure and background combination of the ten Brodatz textures, resulting in a total of 45 test images. Image patches used in training were not used for testing. The benefit of surface attention in eliminating classification errors at the figure boundary was estimated by computing classification accuracies with and without surface attention for the second test dataset mentioned above. Test classification using surface attention was performed in two phases. In the first phase, volitional attention was set at the horizontal center of the input image and offset a little towards the top, similar to the image in Figure 4i. In this phase, surface attention covered the central square figure, and dART inputs on the outer side of the form boundary were suppressed; cf., Equation (A12). All pixels within the attended surface were classified. In the second phase, volitional surface attention was set at a location 96 pixels to the left of its previous location, similar to the image in Figure 4l. The shift in volitional attention resulted in a background-fitting attentional shroud, activating features surrounding the central square figure and suppressing those inside the square. These newly attended pixels were classified, and class labels from the two phases were combined to obtain a final classification; see Figure 5f for an example output. Classification without surface attention was performed pixel-by-pixel over the whole input image in a single phase of processing.

The top half of Table 1 contains classification results for every combination of the training and testing conditions described above on the 10-texture library described earlier. As noted above, the training and testing procedures above were also performed on a 9-texture library obtained by removing one texture material (the Jeans texture image) from the image set. The bottom half of Table 1 contains classification results for this 9-texture library.

This benchmark study leads to two main conclusions: First, training with top-down surface attention results in classification rates similar to training on images with a single texture; compare the first two columns of Table 1. Second, test performance significantly deteriorates when trained without surface attention on the two textures per input image dataset; compare the last column of Table 1 to the first two. These two observations strongly suggest that most of classification performance deterioration is due to mixing of texture features during training. Furthermore, surface attention usually significantly improves test performance; compare rows 2 and 3 of Table 1 for the 10-texture library and rows 5 and 6 for the reduced 9-texture library.

Figure 5 shows an example of dARTEX texture classification output. In particular, Figure 5e shows the best case input image on which 97.6% classification accuracy was achieved by using surface attention.
<table>
<thead>
<tr>
<th>Testing</th>
<th>10-Texture Library</th>
<th>9-Texture Library</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 Textures/Image</td>
<td>1 Textures/Image</td>
</tr>
<tr>
<td>One Texture/Image</td>
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<td>98.1%</td>
</tr>
<tr>
<td>with attention</td>
<td>95.1%</td>
<td>95.9%</td>
</tr>
<tr>
<td>2 Textures/Image</td>
<td>90.6%</td>
<td>92.7%</td>
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<td>with attention</td>
<td>97.6%</td>
<td>98.6%</td>
</tr>
<tr>
<td>2 Textures/Image</td>
<td>95.4%</td>
<td>95.3%</td>
</tr>
<tr>
<td>no attention</td>
<td>90.9%</td>
<td>93.2%</td>
</tr>
</tbody>
</table>

Table 1: Percentage of correctly classified image pixels on Brodatz (1966) microtexture images. Performance was evaluated on two image libraries containing 10 and 9 textures each. The different training and test conditions were based on the number of textures in input images and the presence or absence of top-down surface attention.

Figure 5f shows the corresponding texture label output. Without surface attention, accuracy on the same image was 93.2%. In comparison, Grossberg & Williamson (1999, pp. 1396) reported a 79.5% correct classification rate on a Brodatz texture mosaic. In their ARTEX model, Grossberg & Williamson (1999) used single-texture images for training and did not utilize surface attention. As seen in Figure 5 of Grossberg & Williamson (1999), errors in ARTEX occurred almost exclusively at texture boundaries. On images containing only one texture, Grossberg & Williamson (1999, Table 1) reported 97.1% correct with a spatial pooling window size comparable to dARTEX. As seen in Table 1, dARTEX achieves somewhat better performance (98.1% correct) on the same single-texture Brodatz images. In a related study using the same 10-texture library used here, Greenspan et al. (1994) used a log-Gabor Gaussian pyramid for feature extraction followed by either a k nearest-neighbor algorithm (95% correct), a back-propagation network (96% correct), or a rule-based classifier (ITRULE, 93% correct). In a comprehensive survey of the effects of filter choice on classification accuracy, Randen & Husoy (1999) used a large variety of filters for texture feature extraction followed by a pixel-by-pixel classification. Though their results significantly varied from image to image and from one filter to another, Randen & Husoy (1999, Table 3) reported average 69.1% correct classification rate using 9 tiled texture classes. The 69.1% classification rate was the average performance over all texture images, filter types, and classifier types used in the study; see Randen & Husoy (1999) for further discussion.

While many classification studies target Brodatz (1966) textures, the Randen & Husoy (1999) study is relevant to ours because of two similarities: First, Randen & Husoy (1999) used tiling of abutted textures for input, and second, they utilized disjoint image patches for training and testing. To the best of our knowledge, theirs is also the most comprehensive study of the effect of filter choice on texture classification. Randen & Husoy (1999) noted two issues with many studies of texture classification: First, texture abutment causes learning and classification errors at texture boundaries, and utilization of disjoint image patches for testing and training greatly deteriorates overall classification performance. Second, overall performance is sensitive
to filter choice. Despite the differences between the Randen & Husoy (1999) study and the present one in terms of image scaling, cross-validation method, feature choice, etc., their study is relevant to ours because of the first issue noted above; both studies utilize abutted textures and do not use the same image patches for testing and training. The second issue raised above can in fact be exploited as a useful baseline comparison. Specifically, noting that lack of surface attention in dARTEX greatly reduces the accuracies to an average 75.5% correct (for 9-texture library; see Table 1, column 3, row 6) vs. average 69.1% reported by Randen & Husoy (1999), it is clear that although dARTEX outperforms the averaged performance of a large number of filter and classifier choices, a key reason for the best performance of dARTEX is surface attention; also compare Table 1 columns 1 and 2 to column 3.

As a qualitative description of the role of surface attention in classification, Figures 5g and 5h show average improvement and deterioration, respectively, over all the 45 test images. Figure 5g shows a gray-level map of the total number of times each location in the images was misclassified without surface attention but was correctly classified with attention. Darker pixels in Figure 5g denote higher counts of improvement in classification. In the same color-scale, Figure 5h shows the reverse case, where a previously correct classification was misclassified due to surface attention. This analysis shows that surface attention yields classification improvement along the figure boundary without incurring noticeable deterioration.

2.12 Object Boundary Processing in Natural Images. dARTEX performance on two images from a human-segmented database of images (Martin, Fowlkes, Tal, & Malik, 2001) is shown in Figure 6. dARTEX boundary detection, grouping, and attention produce image boundaries that are in fair correspondence to human segmented boundaries. For the two images used, the first two rows in Figure 6 show object boundaries assigned by human subjects (Figures 6b and 6f), the second moment matrix (2MM) edge detection algorithm (Figures 6c and 6g, Konishi, Yuille, Coughlan, & Zhu, 1999), and dARTEX (Figures 6d, and 6h). With dARTEX, co-operative boundary grouping and the attentional modulation of these grouped boundaries results in relatively strong boundary activity even where the image contrast is fairly low. For instance, consider the vertical boundary of the head of the elephant in the foreground in Figure 6e. The dARTEX output in Figure 6h successfully detects the boundary, while the 2MM boundary detection algorithm in Figure 6g is unable to do so.

Multiple scale processing of dARTEX also has its use in signaling varying amounts of detail about the scene. For example, for the input image in Figure 6e, equilibrium activities of bipole grouping cells at the three successively larger scales signal different aspects of the scene. At the lowest spatial scale, individual surface features are preserved (Figure 6i). Visually, however, the medium scale is the most informative for identifying the elephant (Figure 6j). The largest scale bipole groupings isolate the two animals from the image background (Figure 6k).

While dARTEX yields favorable boundary processing results compared to the feature contrast-based edge detection approach, it still does not encompass many aspects of human vision. For example, dARTEX does not have the figure-ground segregation abilities and the considerable amount of domain specific knowledge used by humans when dealing with natural scenes. An example of the utilization of such domain knowledge can be seen in human segmentations of Figure 6b, where all the human subjects disregarded all of the windows in the building because their task was to segment the major components of the scene and not the finer details. Neither dARTEX nor computer algorithms mentioned here have access to such strategies. For an extension of boundary and surface processing that can explain various figure-ground data, see articles about FACADE theory, e.g., Grossberg (1994, 1997); Grossberg & Swaminathan (2004); Grossberg & Yazdanbakhsh (2005); and Kelly & Grossberg (2000).

3 Simulation of Orientation-Based Texture Segmentation Experiments

dARTEX simulations of the Orientation-Based Texture Segmentation (OBTS) experiments of Ben-Shahar & Zucker (2004) are described in this section.
Figure 6: dARTEX performance on some natural input images from Martin et al., (2001). (a,e) Input images; (b,f) Human segmentation; (c,g) 2MM edge detector algorithm (Konishi et al., 1999); (d,h) dARTEX boundary output generated by adding rectified bipole cell activities over all scales and orientations; (i-k) Bipole activities for each spatial scale added over all orientations, from the smallest (left) to largest (right). The low-contrast boundary at the forehead of the foreground elephant is amplified through bipole grouping and boundary-based attention in (j). The image in (h) is the sum of (j), (k), and (l). Darker pixels signify stronger boundaries for all segmentation outputs. Images in (a,b,c,e,f,g) are from the Berkeley Segmentation Dataset (http://www.cs.berkeley.edu/projects/vision/bsds)
3.1 OBTS Experiments of Ben-Shahar and Zucker (2004). Ben-Shahar & Zucker (2004) used a two alternative, forced choice experiment (2AFC) to investigate the differences in OBTS due to texture element configuration at the boundaries and the role of image orientation gradients. Some example experimental stimuli are shown in Figure 2. The stimulus images were made of a regularly spaced tiling of 21 x 21 bright elongated bars on a dark background. Orientation of the texture bars varied continuously in the vertical direction, except at the wedge-shaped form boundaries, which were defined by an orientation discontinuity. While the horizontal and diagonal limbs of the wedge shapes were due to orientation discontinuity, the vertical limb of the wedge form was due to the image boundary itself. Stimulus images spanned 10° of visual angle.

The horizontal discontinuity line appeared either 2.5° above or below the center of the image, and remained at the same location and orientation throughout the stimulus presentation. The diagonal discontinuity line remained at the same location regardless of the location of the horizontal discontinuity line, giving rise to either a left-pointing or a right-pointing wedge, depending on the location of the horizontal boundary. Examples of left-pointing wedges are shown in Figure 2. The task of the subjects was to report, using a button press, which way the wedge pointed. Stimulus images were presented for 200ms, preceded and followed by masks of randomly oriented bars. Performance accuracy of 75% or more was considered statistically significant. With a vertical orientation gradient \( \nabla \theta \), all bars along the horizontal figure boundary had the same orientation, which abruptly changed on the other side of the boundary.

Ben-Shahar & Zucker (2004) hypothesized that the diagonal discontinuity line in the image did not affect the subjects’ decision process because it maintained the same bar configuration regardless of the location of the horizontal boundary. The two possible responses were therefore due to the location of the horizontal boundary, being either above (for a right-pointing wedge) or below (for a left-pointing wedge) the fixation point. All subjects were pre-trained, and were aware that the discontinuity line determining the response was always horizontally oriented and could occur at exactly one of the two possible locations.

Ben-Shahar & Zucker (2004) defined the Orientation Defined Texture (ODT) by specifying an initial bar angle \( \theta_0 \) at the image co-ordinate origin and a constant orientation gradient \( \nabla \theta \) defined over the whole image. The orientation gradient was kept constant and always in the vertical direction, resulting in a smooth variation in bar orientation from the top to the bottom of the image except at the texture boundaries, where an abrupt change in orientation occurred. The within-region orientation gradient magnitude, denoted by \( \Delta \theta_{\text{within}} \), was parametrically varied from 5° to 30° per degree of visual angle, in steps of 5°. The task difficulty increased with an increase in the angular gradient; texture boundary of Figure 2c (with \( \Delta \theta_{\text{within}} = 5° \)) is easier to detect than in Figure 2f (with \( \Delta \theta_{\text{within}} = 15° \)).

The second parameter in the experiment was the angular discontinuity at the boundaries, denoted by \( \Delta \theta_{\text{between}} \). The parameter \( \Delta \theta_{\text{between}} \) varied from 5° to 90° in steps of 5°. Task difficulty decreased with an increase in this parameter; the texture boundary in Figures 2a is harder to detect (with \( \Delta \theta_{\text{between}} = 30° \)) than in Figure 2c (with \( \Delta \theta_{\text{between}} = 90° \)).

The relation between local bar orientation \( \theta \) and image orientation gradient vector \( \nabla \theta \) gives rise to two scalar fields, or curvatures, defined over the entire image. These curvatures measure the initial rates of change of orientation in directions tangential (the tangential curvature \( k_T \)) and normal (the normal curvature \( k_N \)) to bar orientation at each image location. Specifically, the two curvatures are (Ben-Shahar & Zucker, 2004):

\[
\begin{align*}
  k_T &= \nabla \theta \cdot (\cos(\theta), \sin(\theta)) \\
  k_N &= \nabla \theta \cdot (-\sin(\theta), \cos(\theta)),
\end{align*}
\]

where \( \nabla \theta \) is the image orientation gradient vector, and \( \theta \) is the bar orientation. Operator \( \cdot \) denotes a vector inner product.
As seen in Equation (3.1), texture bar orientation and the two curvatures are intimately linked through the image orientation gradient vector. Furthermore, the two curvatures are co-variant: the value of one completely specifies the other. Specifically, $\Delta \theta_{\text{within}} = \| \nabla \theta \| = \sqrt{k_T^2 + k_N^2}$ (Ben-Shahar & Zucker, 2004). With the image orientation gradient in the vertical direction, the normal curvature $k_N$ is maximal and $k_T$ is zero wherever texture bars are horizontal; see Equation (3.1). Similarly, the tangential curvature $k_T$ is maximal and $k_N$ is zero wherever texture bars are vertical. Orientation gradient discontinuity in the image causes a corresponding discontinuity in the tangential and normal curvatures, denoted by $\Delta k_T$ and $\Delta k_N$, respectively. Furthermore, different relative values of $\Delta k_T$ and $\Delta k_N$ give rise to different bar configurations at the texture boundary. The main goal of the Ben-Shahar & Zucker (2004) study was to relate the curvature discontinuities to OBTS. A complete description of the differential geometric interpretation of orientation defined textures can be found in Ben-Shahar & Zucker (2004). In what follows, a qualitative description is provided of the two curvature discontinuities and resultant bar configurations at the horizontal texture boundary in the experimental stimuli of Ben-Shahar & Zucker (2004).

Three different curvature discontinuity conditions at the horizontal texture boundary were explored by Ben-Shahar & Zucker (2004). The first combination was defined by $\Delta k_N = 0$, the second by $\Delta k_T = 0$, and the third by $\Delta k_T = \Delta k_N$. In a given trial, the quantities $\nabla \theta$, $\Delta \theta_{\text{between}}$, $\Delta k_N$, and $\Delta k_T$ completely specified the stimulus image, and were kept constant throughout the stimulus presentation. The following discussion assumes a vertical orientation gradient vector $\nabla \theta$.

In the first curvature discontinuity combination, termed the $\Delta k_T = \text{max}$ condition, $\Delta k_T$ is maximal and $\Delta k_N$ is zero at the horizontal boundary. As seen in Equation (3.1), the two curvatures are continuous functions of the orientation gradient over the whole image, except at the form boundaries defined by discontinuity in orientation. The only way $\Delta k_N = 0$ can be achieved at the horizontal boundary is if $k_N$ remains the same at points equidistant in the vertical direction from the horizontal boundary on its either side. This requirement, along with the continuity of curvatures on either side of the horizontal boundary, requires that $k_N$ pass through a maximum and $k_T$ simultaneously pass through zero, meaning the horizontal bar orientation at the horizontal boundary. Figure 2a shows an example of this condition, where bars on either side of the horizontal boundary deviate from horizontal orientation by equal angular amounts (approximately $\Delta \theta_{\text{between}}/2$) but in opposite directions. In other words, but for the angular discontinuity, the orientation gradient would have given rise to horizontal bar orientations at the horizontal form boundary. For the $\Delta k_T = \text{max}$ condition, as $\Delta \theta_{\text{between}}$ increases, the bars become increasingly oblique on either side of the boundary.

The second curvature discontinuity condition is defined as $\Delta k_T = \Delta k_N$. For this condition, by a similar argument as above and referring to Equation (3.1), the orientation at the horizontal boundary passes through an oblique, or $45^\circ$, orientation. Figure 2c shows an example of this condition, where bars on either side of the horizontal boundary deviate by an equal angular amount from the oblique orientation.

The third curvature discontinuity combination, termed the $\Delta k_N = \text{max}$ condition, is similar to the first except in this case $\Delta k_N$ is maximal and $\Delta k_T = 0$. In this condition, angular flow at the horizontal boundary passes through the vertical orientation instead of the horizontal orientation; see the horizontal boundary in Figure 2b.

Using the curvature discontinuity conditions described above, Ben-Shahar & Zucker (2004) found that the same amount of $\Delta \theta_{\text{between}}$ resulted in different perceived boundary saliencies when the flow of oriented bars was interrupted in different ways. This asymmetry was most pronounced at small within-region orientation gradient magnitudes ($\Delta \theta_{\text{within}} \leq 10^\circ$). For these low gradient amounts, the $\Delta k_T = \text{max}$ condition was salient even for low values of $\Delta \theta_{\text{between}}$; for example, in Figure 2a the wedge form can be clearly seen with $\Delta \theta_{\text{within}} = 5^\circ$ and $\Delta \theta_{\text{between}} = 30^\circ$. Despite the same amount of boundary discontinuity, however, the wedge form in $\Delta k_N = \text{max}$ condition is much harder to see; horizontal boundaries in Figures 2a appear clearer than in 2b. For small $\Delta \theta_{\text{within}}$ and $\Delta \theta_{\text{between}}$, the $\Delta k_T = \text{max}$ conditions were even more salient.
than the $\Delta k_T = \Delta k_N$ conditions, but the $\Delta k_T = \Delta k_N$ configurations eventually became stronger with increasing $\Delta \theta_{between}$. This can be seen in the data plots of Figure 3a, where the detection accuracies for the $\Delta k_T = \text{max}$ (the blue curve with boxed points) are higher than any other condition at low values of $\Delta \theta_{between}$. However, as $\Delta \theta_{between}$ becomes large, the $\Delta k_T = \Delta k_N$ condition becomes more salient; see the green curve with crossed points in Figure 3a. As noted earlier in this section, an increase in orientation gradient magnitude $\Delta \theta_{within}$ is detrimental to successful boundary detection; note the drop in accuracies as $\Delta \theta_{within}$ progressively increases in Figures 3a through 3f. Specifically, salience of the $\Delta k_T = \text{max}$ configurations diminishes for $\Delta \theta_{within} = 10^\circ$ compared to $\Delta \theta_{within} = 5^\circ$, and ultimately disappears with increasing orientation gradient magnitude $\Delta \theta_{within}$; see the blue curves with boxed points in Figures 3a through 3f. For $\Delta \theta_{within} = [15, 20]$, only the $\Delta k_T = \Delta k_N$ conditions were detectable even for large $\Delta \theta_{between}$ values, see Figures 3c and 3d, which also eventually disappears, see Figures 3e and 3f.

In the experiment of Ben-Shahar & Zucker (2004) described above, parallel configurations that arose with $\Delta k_T = \Delta k_N$ and $\Delta \theta_{between} = 90^\circ$, where bars on one side of the horizontal boundary were horizontal, were found to be more salient than other configurations; compare horizontal boundary strengths of Figures 2d, 2e, and 2f, where the boundary in Figure 2f is the strongest. As a second experiment, Ben-Shahar & Zucker (2004) further investigated the relative salience of the $\Delta k_T = \Delta k_N$ configurations to parallel configurations. In this second experiment, $\Delta \theta_{between}$ was set at $45^\circ$. The purpose of this experiment was to investigate whether parallel configurations were always salient regardless of the specific values of $\Delta \theta_{within}$. Ben-Shahar & Zucker (2004) found that, at low angular gradient magnitudes ($\Delta \theta_{within} \leq 10^\circ$), parallel configurations had higher detection accuracy. However, with higher angular gradients ($15^\circ \leq \Delta \theta_{within} \leq 20^\circ$), the $\Delta k_T = \Delta k_N$ configurations became more salient, suggesting that the abrupt termination of the “flow” was more salient.

Possible reasons for the salience asymmetries due to boundary configurations and changes in $\Delta \theta_{within}$ are discussed in Section 3.3 using dARTEX simulations.

### 3.2 Texture Boundary Contrast Measure for the OBTS Task Simulation

In order to compare model performance to perceptual data, the following boundary contrast measure was used:

$$S = \mu \frac{E_{Lower} - E_{Upper}}{\nu + E_{Lower} + E_{Upper} + F} + 50,$$

(3.2)

where $\mu$ and $\nu$ are constant numbers, and $E_{Lower}$ and $E_{Upper}$ are bipole cell activities pooled over horizontal bands centered at each possible boundary location. Factor $F$ in the above equation is average boundary activity over the whole image. The contrast measure above is derived from the equilibrium solution of a shunting on-center, off-surround network (Grossberg, 1973, 1980). The contrast measure hypothesizes that subjects paid spatial attention to boundary activities at the two possible horizontal discontinuity locations, horizontal being the response-determining boundaries, and chose the location with greater activity. The probability of correct response is thus hypothesized to be proportional to the contrast between boundary activities at the two attended spatial locations. The surround inhibition factor $F$ in Equation (3.2) measures average boundary activity in the whole image. Section A10 mathematically defines the terms in this salience measure.

Two methods of computing the boundary activities $E_{Lower}$ and $E_{Upper}$ in the boundary contrast measure are compared. The two methods differ in the manner in which bipole activities are pooled across orientations within the upper and lower possible boundary regions. The first method of pooling uses a spatial attentional gain (Johnson & Yantis, 1995; Posner, 1980; Pylyshyn & Storm, 1988; Shaw, 1982) where total boundary grouping activity, summed over all orientations, is compared between two possible boundary regions; see Equation (3.2) above. This pooling concept mathematizes the fact that the subjects knew that the correct response could be determined completely by the location of the horizontal discontinuity line, and that the line could appear at exactly one of the two possible locations in the scene.
The second method differentially weights boundary orientations in addition to spatial locations (Cavanagh, 1992; Corbetta et al., 1990; Wolfe et al., 1989). The horizontal orientation is given the most weight, with a Gaussian fall-off for nearby orientations (Equation (A39)). This boundary contrast measure incorporates the fact that the response-determining boundaries are always horizontal, and assumes that subjects paid attention to the two possible regions and looked for a horizontal line within them. Wolfson & Landy (1995) used a similar scheme of assigning more weight to a specific orientation of their second-order filters to explain the increased salience of parallel-perpendicular bar configurations at texture boundaries.

3.3 Simulation of Orientation-Based Texture Segmentation data. dARTEX simulations clarify the role of boundary grouping and attentional amplification of well-grouped boundaries in Orientation-Based Texture Segmentation (OBTS). For the OBTS simulations, the volitional spatial attention (I_{pq} in Equation (A33)) was kept fixed at the image center, where the experimental subjects were instructed to fixate. In the interest of conserving computer simulation time, the dART network was kept untrained. We have verified that an appropriately trained dART network does not alter the simulation outputs for \( \Delta \theta_{within} = 5^\circ \).

Figure 2 shows simulation outputs of some of the interesting experimental stimuli. Figure 2a shows a stimulus with \( \Delta k_T = max, \Delta \theta_{within} = 5^\circ, \) and \( \Delta \theta_{between} = 30^\circ \). In this case, texture elements are roughly aligned with the horizontal texture boundary and the orientation discontinuity detected by the competitive stages in V2 is readily grouped by the horizontally oriented bipole cells. The automatic boundary attention to the LGN (Section 2.6) further amplifies these boundaries while suppressing their neighboring elements by acting on the surround kernels in the LGN. As a result of this amplification of boundary elements at the LGN, the activities of simple cell filters at the boundaries are higher compared to their neighborhood. This enhanced contrast in the simple and complex cell activities supplements the orientation contrast, resulting in further amplification of the boundary. Thus, grouping and feedback produce a strong boundary even for low values of \( \Delta \theta_{between} \). As seen in Figures 7b and 7c, regardless of the method of boundary activity pooling, strong boundary contrast develops for the \( \Delta k_T = max \) configuration, which is plotted with boxed points and blue curves in Figure 7.

Figure 2b shows a stimulus with the same orientation parameters (\( \Delta \theta_{within} = 5^\circ, \Delta \theta_{between} = 30^\circ \)) as above but with \( \Delta k_N = max \). For this case, the texture bars are almost orthogonal to the boundary. This configuration results in very weak grouping in the horizontal bipole orientation. Furthermore, bipole grouping in the vertical orientation spreads the activity orthogonal to and away from the texture boundary, resulting in a thick band of increased activity around the texture boundary at the LGN. Neither the center-surround filters in the LGN, nor the spatial competitive stages in V2, can sharpen this diffuse boundary activity. As a result, the total bipole activity at the horizontal figure boundary is not very different from the average activity over the whole image. Extra weight to the horizontal bipole orientations in the boundary contrast measure only decreases the weighted bipole activity at the boundary, resulting in a further deterioration of boundary salience; compare data points in Figures 7b and 7c for \( \Delta \theta_{between} = 30^\circ \) and \( \Delta k_N = max \) condition, plotted with circled points and red curves.

Figure 2c shows a stimulus with very strong segmentation. In this case, with \( \Delta k_T = \Delta k_N \), the orientation gradient is low (\( \Delta \theta_{within} = 5^\circ \)), and the boundary discontinuity amount is maximal (\( \Delta \theta_{between} = 90^\circ \)). Here, orientation contrast is readily detected by the competitive stages in V2, and the co-aligned boundary features are strongly grouped by the horizontally oriented bipole cells. Furthermore, feedback modulation of the LGN increases the activities at the horizontal boundary. In fact, of all the examples simulated with \( \Delta \theta_{within} = 5^\circ \), this configuration yielded the strongest boundaries; compare dARTEX simulation outputs of the three conditions for \( \Delta \theta_{between} = 90^\circ \) in Figure 7b.

The grouping and boundary-based attentional processes described above also help to explain rest of the outputs in Figure 7b. As described in Section 3.1, the \( \Delta k_T = max \) condition bars start out parallel to the horizontal boundary and increasingly become oblique on both sides of the boundary as \( \Delta \theta_{between} \) increases. On the other hand, the \( \Delta k_T = \Delta k_N \) configurations start out roughly oblique to the boundaries and gradually become parallel to the boundary on one side as \( \Delta \theta_{between} \) increases. Lastly, the \( \Delta k_N = max \) configurations
Figure 7: Boundary attention and horizontal cooperative grouping are necessary for boundary processing. (a) Experimental data of Ben-Shahar and Zucker (2004). Green curve with crossed points: $\Delta k_T = \Delta k_N$, blue curve with boxed points: $\Delta k_T = \text{max}$, red curve with circled points: $\Delta k_N = \text{max}$ and $\Delta \theta_{\text{within}} = 5^\circ$. Vertical axis: detection accuracy, horizontal axis: boundary discontinuity amount $\Delta \theta_{\text{between}}$. (b) With feedback and grouping operational and horizontal bipole orientations receiving the most weight with a Gaussian falloff in orientation, the data fit is very close to the observed results. (c) Same as part b, but with the same weight applied to all bipole orientations. (d) With no boundary-based attention modulating the LGN, the salience actually drops at high $\Delta \theta_{\text{between}}$ and $\Delta k_T = \text{max}$ due to the lack of boundary amplification that enable bipole grouping in horizontal orientation. (e) Bipole grouping disabled, and the V2 competitive stage outputs constitute feedback to LGN. Boundary salience does not increase with increasing $\Delta \theta_{\text{between}}$ for $\Delta k_T = \text{max}$ due to lack of boundary amplification by bipole grouping. (f) Same as (e) but with all orientations added with equal weight. Crossover of salience curves vanishes. This output is very similar to the predicted output of the Filter-Rectifier-Filter model containing two stages of filters with intermediate point-wise nonlinearity.
start out with bars perpendicular to the horizontal boundary on both sides and gradually assume the same oblique orientation on both sides of the boundary as the $\Delta k_T = max$ case. The $\Delta k_T = max$ configurations, therefore, initially receive a boost in the boundary strength through grouping, but this advantage diminishes with increasing $\Delta \theta_{between}$, as the horizontal filter activity gradually decreases. However, with increasing $\Delta \theta_{between}$, boundary contrast, and therefore the boundary-based attentional feedback to the LGN, increase in magnitude, which amplifies the end cuts (see Section 2.4), thus retaining the horizontal boundary grouping. For the $\Delta k_T = \Delta k_N$ configurations, boundary elements become increasingly parallel to the horizontal boundary with increasing $\Delta \theta_{between}$, greatly increasing the dipole grouping and feedback enhancement of LGN features. Salience curves therefore cross in Figure 7b, where $\Delta k_T = \Delta k_N$ configuration saliences surpass $\Delta k_T = max$ at higher $\Delta \theta_{between}$ values. Lastly, while saliencies for $\Delta k_N = max$ configurations do increase with increasing $\Delta \theta_{between}$, they are never strong enough to surpass either of the other configurations due to the lack of grouping and feedback processes working in concert as described earlier.

The complete set of OBTS simulations is shown in Figure 3. As image orientation gradient magnitude $\Delta \theta_{within}$ increases, activities of the oriented filters of a given orientation become increasingly non-uniform over the whole image. As a result, the spatial competitive stages in V2 begin to fail to suppress activities in the region interiors, and the boundary contrast diminishes rapidly. With increasing $\Delta \theta_{within}$, boundary activity contrast for all configurations decreases regardless of the amount of $\Delta \theta_{between}$, and the overall image “clutter” increases; see simulation outputs of Figures 2d, 2e, and 2f, where background activity is higher with $\Delta \theta_{within} = 15^\circ$ than in Figures 2a, 2b, and 2c with $\Delta \theta_{within} = 5^\circ$. The boundary contrast measure in Equation (3.2) is penalized by this image clutter through a long-range inhibitory term $F$, denoting average boundary activity in the image. Nevertheless, grouping and feedback modulation continue to play a role, and the $\Delta k_T = \Delta k_N$ configurations for higher values of $\Delta \theta_{between}$, where bars are roughly parallel to the horizontal boundary, do eventually surpass detection thresholds for $\Delta \theta_{within} \leq 20^\circ$.

To control for model parameter overfitting, dARTEX parameters and the salience measure were tuned using stimuli with $\Delta \theta_{within} = [5, 15, 25]$. The goodness of data fit can be inferred in the $\Delta \theta_{within} = [10, 20, 30]$ simulations.

As in the second experiment of Ben-Shahar & Zucker (2004), the $\Delta k_T = \Delta k_N$ simulations were also compared to parallel configurations where bars on the inside of the horizontal boundary were parallel to the boundary. For this comparison, boundary contrasts were computed for $\Delta \theta_b = 45^\circ$ and $\Delta \theta_{within} = [5, 10, 15, 20]$. Ben-Shahar & Zucker (2004) observed that the parallel configurations were more salient than the configurations with $\Delta \theta_{within} = [5, 10]$ but became less salient with $\Delta \theta_{within} = [15, 20]$. The percentage detection accuracy difference between the two conditions in the experiments was $[12, 12, −4, −10]$ for $\Delta \theta_{within} = [5, 10, 15, 20]$, respectively, with stronger parallel configuration assuming positive values. dARTEX output differences, on the other hand, were $[3.1, 1.1, −2.1, −4.5]$ percent for $\Delta \theta_{within} = [5, 10, 15, 20]$, respectively, matching the observed relative saliences of the two configurations.

For textures with $\Delta \theta_{within} = [15, 20]$, the $\Delta k_T = \Delta k_N$ bar configurations at the boundaries look like Ts. For the same parameter values, the parallel configuration looks like horizontally oriented Vs, with one arm of the V parallel to the boundary. The discrepancies in the exact percentage values between dARTEX output and observed data may be due to the inherent importance of junctions for figure-ground segregation. We suspect additional mechanisms not simulated in dARTEX, such as the angle cells simulated by Grossberg & Swaminathan (2004), may be contributing towards an even heightened salience of the T configurations. For the smaller differences in the simulated values between the two configurations for $\Delta \theta_{within} = [5, 10]$, additional amplification of boundaries due to a V2 to V1 modulatory feedback (Grossberg & Raizada, 2000), not implemented in dARTEX, may be responsible.

3.4 The Role of Boundary-Based Attention and Horizontal Bipole Grouping. The consequences of inactivation of either boundary grouping or boundary-based attention are shown in Figures 7d and 7e. With the boundary-based attentional amplification of the LGN turned off (Figure 7d), the obliquely oriented elements at the boundary for high values of $\Delta \theta_{between}$ are not contrast-enhanced. This results in much diminished
salience at high values of $\Delta \theta_{\text{between}}$ in the $\Delta k_T = \text{max}$ configurations.

With the bipole grouping switched off, all curves are generally lower, as seen in Figure 7e. Furthermore, contrary to the experimental data, the contrast measure in Equation (3.2) does not increase for $\Delta k_T = \text{max}$ or $\Delta k_N = \text{max}$, as $\Delta \theta_{\text{between}}$ increases. This is due to the lack of amplification of horizontal boundary orientations by bipole grouping. In the plots of Figures 7d and 7e, extra weight was applied to the horizontal orientations in the salience measure, as described in Equation (A36). Since grouping was inactive in Figure 7e, the V2 competition stage outputs, and the vertical axis was rescaled to match the other plots.

With bipole grouping disabled and equal weight given to all orientations while pooling V2 competition stage outputs, the salience symmetries due to boundary configurations disappear, as seen in Figure 7f. Bipole grouping is a prime driver for producing the salience asymmetries: With the same weight applied to all orientations, with bipole grouping enabled, the relative boundary contrasts are preserved in Figure 7c but not in Figure 7f, where the bipole grouping is disabled.

### 4 Related Work

Many models of texture segregation follow the general Filter-Rectification-Filter (FRF) scheme of two filter stages with an intermediate point-wise rectifying nonlinearity (Bergen & Landy, 1991; Grossberg & Mingolla, 1985b; Grossberg & Williamson, 1999; Malik & Perona, 1990; Sutter et al., 1989; Wilkinson & Wilson, 1998). A related class of models utilizes oriented filter outputs, similar to the first stage of filtration in FRF, for local texture classification (Fogel & Sagi, 1989; Grossberg & Williamson, 1999; Jain & Farrokhnia, 1991; Rubner & Tomasi, 1999).

For example, Malik & Perona (1990) used a boundary-based approach for computing texture gradients and were able to fit psychometric functions of texture discriminability. Instead of using orientational competition as in Grossberg & Mingolla (1985b) and dARTEX, Malik & Perona (1990) used a winner-take-all competition in orientation at every image pixel. The dARTEX simulations of Orientation-Based Texture Segmentation (OBTS) data presented in this paper show that the graded responses from all oriented channels, and attentional feedback derived thereof, are required for a quantitative data fit. Furthermore, dARTEX uses mechanisms beyond FRF, including bipole grouping and boundary attention, that enable quantitative simulations of OBTS data.

Another texture classification approach has utilized Markov random fields to probabilistically estimate and cluster texture features (Chellappa & Chatterjee, 1985; Cross & Jain, 1983; Manjunath & Chellappa, 1991; Mao & Jain, 1992; Zhu, Wu, & Mumford, 1998). Yet another approach utilizes probabilistic or data-driven methods for nonparametric estimation of filters, or for combining filter responses (Malik, Belongie, Leung, & Shi, 2001; Martin et al., 2001; Puzicha, Hoffmann, & Buhmann, 1997; Varma & Zisserman, 2003). While all these approaches result in good texture classification performance for isolated texture patches, they do not have the explicit means to utilize top-down attention to guide texture learning or to prevent misclassifications at the boundaries due to feature mixing.

A survey of filter energy-based methods, especially the FRF, and their relation to human texture segmentation may be found in Bergen & Landy (1991). Some of the more recent texture-based image segmentation attempts also follow a similar filter-based approach (e.g., Arivazhagan & Ganesan, 2003; Krumm & Shafer, 1994). In addition to utilizing filter contrast detection, dARTEX also utilizes boundary grouping and boundary-based feedback for enhancing the detected boundaries in a context-dependent way. These additional processes are responsible for the sensitivity to local bar configurations at the boundaries in OBTS, which are difficult to explain with FRF without relying on parameters extrinsic to the image set used.

The ARTEX model of Grossberg & Williamson (1999) utilized boundary processing to drive local texture classification. In the ARTEX model, a Boundary Contour System (Grossberg & Mingolla, 1985a, 1985b) acts as a front-end to a Gaussian ARTMAP (Williamson, 1996) classifier for pixel-by-pixel texture classification. The dARTEX model differs from ARTEX in important ways. First, the dART network used here is more tightly integrated with boundary processing, so that learned texture feature expectations from
the dART network directly influence the subsequent dynamics and the final output of the boundary system. Second, as we saw in Section 2.11, top-down surface-mediated attentional shrouds guide attentive classification and texture learning. This method substantially improves classification performance in the benchmark studies and also helps boundary processing. Third, dART network in the current model accomplishes preliminary local texture categorization and is sensitive to image scale and orientation. In contrast, ARTEX models texture categorization in the IT cortex and addresses scale-and-orientation independent texture classification using long-range image attributes like surface brightness.

Image processing approaches that combine region (cf., surface) and edge (cf., boundary) based techniques are becoming increasingly popular. For a review, see Munoz, Freixenet, Cufi, & Marti (2003). For example, Paragios & Deriche (2002) used a filter-based technique to recognize texture and used the recognition information to repel figure boundary contours from uniformly textured regions. Mirmehdi & Petrou (2000) used color and texture information to develop initial estimates of figure boundaries, which were refined using iterative re-classification at progressively smaller spatial scales. Martin et al. (2001) used a combination of texture, color, and luminance contrast to partition image pixels into regions of uniform texture. All of these approaches are similar to dARTEX in that they begin with a hypothesis about the texture boundary locations which are then refined to improve performance through a combination of region and boundary information. In dARTEX, the hypothesis about figure boundaries leads to surface attention that prevents feature mixing at the boundaries. Texture feature expectations from dART, in turn, result in image noise suppression that improves form boundary processing. dARTEX thus makes explicit the role of top-down spatial and object attention and the ways in which boundary and region-based processing may interact in a laminar cortical framework. The other models mentioned above do not explicitly address these issues.

Thielscher & Neumann (2003) have proposed a texture boundary processing model that is more similar to dARTEX boundary processing. In their model, top-down, modulatory, boundary feedback from V4 to prior cortical areas was shown to be necessary for orientation-defined texture boundary processing. The goal of their model was to provide a qualitative explanation of the fact that textures with higher image orientation gradient require a correspondingly higher orientation contrast at the boundary for successful segregation (Nothdurft, 1985, 1992). Since the Thielscher & Neumann (2003) model predates the observations of Ben-Shahar & Zucker (2004), it is not known whether it can quantitatively fit the complete OBTS experiments. The dARTEX model, although similar in spirit, differs from that of Thielscher & Neumann (2003) in two major ways. First, dARTEX uses multiple scales of interaction at each processing stage which get successively larger in the hierarchy, and the scale channels interact via boundary and surface feedback. The Thielscher & Neumann (2003) model, on the other hand, uses a single scale of processing which gets larger with each successive stage. In dARTEX the smallest scale groups the texture elements by their proximity in space and similarity in orientation, while the larger scales compute figure boundaries and corners using the same network interactions. Similar information is available in the Thielscher & Neumann (2003) model, but at different stages of processing. Second, dARTEX utilizes top-down surface attentional shrouds to provide a self-supervising signal for the dART module to bind local feature views into texture categories. Surface attention in dARTEX thus closes the loop between the bottom-up, pre-attentive, boundary processing and the top-down, modulatory, attentive learning of texture (Grossberg, 2003). The Thielscher & Neumann (2003) model does not include texture learning or classification and has not been used to address the role of top-down surface attention for texture classification. On the other hand, the two models share many common properties and address similar perceptual data using feature contrast-based boundary finding, modulatory feedback for figure boundary enhancement, and long-range boundary grouping using bipole cells. The two models have also been inspired by the same prior work on how the laminar circuits of the visual cortex lead to visual percepts, in particular by the BCS/FCS theory (Grossberg & Mingolla, 1985a, 1985b) and the 3D LAMINART model (Grossberg, 2003; Grossberg & Raizada, 2000; Raizada & Grossberg, 2003).
5 Discussion and Conclusions

The visual system is capable of learning to recognize individual attributes of objects, e.g., surface texture type, as well as the global shape of an object. At the same time, the visual system can merge distinct types of information based on task requirements. Thus, the vision problem includes aspects of data differentiation as well as integration. A major computational question is as yet open: How does the visual system learn and store both local and global attributes of the visual scene, namely, such local properties as texture, surface curvature, and orientation, and such global properties as the 3D structure of objects. Also, how are these attributes fused to recognize objects?

This article presents the dARTEX model to propose aspects of how the primary visual cortex may carry out texture classification and object boundary processing. The model is interpreted in terms of laminar interconnectivity in the primary visual cortex. The model also assigns specific functional roles to modulatory corticocortical and corticogeniculate feedback connections involved in surface and boundary-based top-down attention. A unique computational feature of dARTEX is its ability to combine object boundary and local texture feature computations in a common, biologically plausible framework. Furthermore, dARTEX generates top-down spatial attentional shrouds using emergent, long-range object boundaries that direct attention to, and enables the learning of, textures that belong to particular objects. Such attentional processing was shown to improve both texture classification and object boundary processing performance. When combined with other ART studies that show how object boundaries and surface properties may be used to categorize properties of object form (e.g., Bradski & Grossberg, 1995; Carpenter & Ross, 1995; Carpenter & Grossberg, 1987; Carpenter et al., 1992, 1991a), a unified ART system for classifying both local and global object properties at multiple levels of the visual system can be discerned.

The study by Ben-Shahar & Zucker (2004) showed how tangential and normal curvatures and their discontinuities are intimately linked to Orientation-Based Texture Segmentation (OBTS). Their model attempted to explain OBTS using these curvatures and their discontinuities at the texture boundaries as intrinsic image parameters. Specifically, they showed that the textures segregated most readily when discontinuities in both the curvatures were simultaneously maximized. They also showed that the two curvatures and their discontinuities are an efficient way of systematically describing and studying a large class of Orientation Defined Textures (ODTs). In the process of describing ODTs with the help of curvatures, Ben-Shahar & Zucker (2004) also put forward a strong case against models of OBTS that detect discontinuities in filter energy and rely on amplification of filter activities based on element orientation relative to the boundaries (e.g., Wolfson & Landy, 1995). In their paper, Ben-Shahar & Zucker (2004) pointed out two objections to using the boundary for selecting the features for amplification or assigning extra weight during salience computation. The first objection was the “chicken-and-egg problem”, where the outcome of the processing – namely, the orientation of the texture boundary – was needed as an input to select which features were assigned the most weight. The second, and more serious, problem was that, even if such selection were allowed, the boundary features may get amplified simply based on their absolute orientation, without any selectivity for their relation to other features away from the boundary. These other features are known to affect segmentation, regardless of whether they are characterized by curvature (Ben-Shahar & Zucker, 2004), orientation variability (Wolfson & Landy, 1998), or arrangement (Beck, 1982; Grossberg & Mingolla, 1985b). Ben-Shahar and Zucker (2004) further argued that such modifications to the energy-based model do not suffice to explain their whole suite of results, especially the crossover of curves for certain image orientation gradients but not for others; see Figure 3.

While fitting the OBTS data of Ben-Shahar & Zucker (2004), dARTEX alleviates most of the concerns about modifying the Filter-Rectifier-Filter (FRF) model raised earlier. While encompassing a FRF computation, dARTEX also includes long-range, recurrent boundary and surface processes, top-down spatial attention that fits the shape of an object surface, and automatic top-down attention that selectively enhances only the features that lie on a texture boundary by an amount proportional to the boundary grouping strength.
Through boundary-based attention derived from bipole cells, dARTEX amplifies only the image features that group well, and at an appropriate spatial scale, lie on the figure boundary; also see Figure 2 for examples of how this automatic attention leads to boundaries that mimic the percepts.

Sensitivity to image orientation gradient arises in dARTEX through two factors: First, at high orientation gradients, the feature contrast detection stage in V2 is unsuccessful in suppressing featural activity in the figure interior. As a result, the activity difference between texture boundary grouping and individual bar grouping decreases, resulting in no net LGN features amplification through boundary feedback. The second factor is the formulation of the boundary contrast measure, which supplements the first one: At high orientation gradients, the contrast measure is low because the boundaries due to feature contrast grouping are roughly the same as boundaries linking individual texture bars.

Much in the spirit of Wolfson & Landy (1995), the OBTS boundary contrast measure used here applies more weight to the horizontal boundary orientation. Such an explicit weighting applied to spatial locations and orientations of boundaries may seem at first to be subject to the same “chicken-and-egg” problem. However, additional mechanisms are hypothesized to play a role in this task-specific modulation of orientations. For example, object attentional modulation that weights boundaries at certain locations or orientations can be computed using center-surround computations much in the spirit of the two competitive stages of Grossberg & Mingolla (1985b), wherein the attended spatial locations are winners of a spatial competition over multiple trials due to the presence of strong boundaries at those locations. Similarly, the horizontal orientation would always win in an orientational competition at these spatial locations, since the form boundaries are always horizontal. As seen in the V2 layer 2/3 bipole cell activities plotted in Figure 2, even without the task-specific spatial and orientational attentional modulation, the pre-attentive grouping and automatic, boundary-based attentional feedback produce strong boundaries at the correct locations and orientations. Large-scale spatial and orientational competition activated by bipole inputs over multiple trials may thus lead to top-down spatial attention to boundaries during segmentation, further amplifying the differences due to element configuration, and producing a quantitative data fit. Also compare dARTEX simulations in Figures 7b (with higher weight in the horizontal orientation) and 7c (with equal weight to all orientations) that preserve the crossovers in the experimental data in Figure 7a.

While fitting the OBTS data of Ben-Shahar & Zucker (2004), the dARTEX model also outperforms related texture classification approaches (Grossberg & Williamson, 1999; Randen & Husoy, 1999). Improved performance in texture classification is due to the ability of top-down surface attention to eliminate feature mixing at form boundaries. Emergent form boundary completion in response to noisy images is also facilitated by the feature noise rejection afforded by dART-based feature match during attentive texture classification.

To conclude, dARTEX attempts to clarify the roles of boundary-mediated object attention and surface-mediated spatial attention. Boundary-mediated object attention is critical for object form processing, while surface-mediated spatial attention is critical in local surface feature learning and recognition. In the process of clarifying the roles of these processes, dARTEX supports the claim that boundaries and surfaces are the units of visual attention (Grossberg, 1999a, 2003). Boundary-mediated attention in dARTEX is shown to proceed in two parts: In the automatic part, pre-attentively computed boundaries amplify and hold features that meet long-range boundary hypotheses through feedback that reaches the LGN. The task-specific part of the boundary-mediated attention further amplifies boundaries at the attended spatial locations. This way of computing boundary mediated attention was shown to quantitatively explain the whole range of OBTS data from Ben-Shahar & Zucker (2004).

Surface-mediated attention in dARTEX proceeds in a similar fashion, but subserves a complementary role: Surfaces identified by pre-attentive boundary-gated filling-in bid for spatial attention. In the absence of a volitional surface selection signal, surfaces with the highest filled-in activity win spatial attention automatically. In the task-specific part of spatial attention, however, a volitional focus of attention, similar to task-specific boundary attention, can bias the competition in favor of the attended surface. A form-fitting surface
attentional shroud from the spatial attention stage leads to a surface-(spatial attention) resonance, that binds multiple texture views from the attended surface into local texture categories learned by the dART network. Experiments on perceptual learning have shown how visual task performance can alter the detection thresholds for elementary image features like orientation and local motion (Hochstein & Ahissar, 2002; Watanabe, Nanez, & Sasaki, 2001). Some of these improvements are retinal location specific, strongly suggesting that these improvements occur at early stages of the visual hierarchy (see Ahissar & Hochstein, 2004, for a survey), and perhaps at the very locations of feature representation (Grossberg, 1999a, 2003). In a similar vein, the ARTSCAN model of Fazl et al. (2005) shows how the same form-fitting surface attentional shroud binds different object views into view-invariant object categories at later stages of the visual cortical hierarchy. A combination of the dARTEX model and the ARTSCAN model thus shows how boundary- and surface-based attention can bind, amplify, and maintain the activity of relevant features while they are learned throughout the visual hierarchy.
Appendices

A System Equations

This section mathematically describes the dARTEX model. Parameter values used in the simulations immediately follow the equation descriptions.

Each model neuron is typically modeled as a single voltage compartment in which the membrane potential, \( v \), is given by

\[
C_m \dot{v} = -(v - E_{\text{leak}})g_{\text{leak}} - (v - E_{\text{excit}})g_{\text{excit}} - (v - E_{\text{inhib}})g_{\text{inhib}},
\]

(A1)

where \( C_m \) is the membrane capacitance, the \( E \) terms represent reversal potentials, \( g_{\text{leak}} \) is a constant leakage conductance, and the time-varying conductances \( g_{\text{excit}} \) and \( g_{\text{inhib}} \) represent the total inputs to the cell (Grossberg, 1973; Hodgkin, 1964). Most of the following network equations are instances of this general membrane equation, where, for simplicity, the capacitance term \( C_m \) was set equal to 1, the leakage conductance is relabeled as \( g_{\text{leak}} = A \), the excitatory and inhibitory reversal potentials are relabeled as: \( E_{\text{excit}} = B \) and \( E_{\text{inhib}} = -C \), and the leakage reversal potential is set to \( E_{\text{leak}} = 0 \). Then Equation (A1) can be rewritten as a membrane, or shunting equation

\[
\dot{v} = -Av + (B - v)g_{\text{excit}} - (v + C)g_{\text{inhib}},
\]

(A2)

where \( A \) is a constant decay rate, \( B \) is an excitatory saturation potential, \( g_{\text{excit}} \) is the total excitatory input, \( C \) is a hyperpolarization parameter, and \( g_{\text{inhib}} \) is the total inhibitory input.

Throughout the dARTEX description, subscripts \( ij \) or \( pq \) denote two dimensional Cartesian image coordinates \((i, j)\) and \((p, q)\), respectively. Subscript \( s \) is reserved for spatial scale, and subscripts \( k \) and \( r \) are reserved for orientations.

Unless otherwise noted, two-dimensional isotropic Gaussian spatial kernel is denoted by \( G_{pqij,\sigma(s)} \). In particular, Gaussian spatial kernel \( G_{pqij,\sigma(s)} \) for position \((p, q)\) and scale \( s \) is defined as:

\[
G_{pqij,\sigma(s)} = \frac{1}{2\pi\sigma^2(s)} \exp\left( -\frac{(p - i)^2 + (q - j)^2}{2\sigma^2(s)} \right),
\]

(A3)

where the kernel \( G_{pqij,\sigma(s)} \) is centered at position \((i, j)\) and has a scale-dependent spatial variance \( \sigma(s) \). Unless otherwise noted, all kernels are normalized to add to 1. All kernel parameters are reported in units of image pixels, and all input images used for simulations are 256 \( \times \) 256 pixels wide.

The operator \([\cdot]^+\) denotes half-wave rectification.

All simulations were carried out using the Matlab simulation package (version 6.5, mathworks.com). All but three model processing stages were explicitly solved for their equilibrium values in order of their activation in the model hierarchy. The remaining three stages, namely, the bipolar, surface filling-in, and surface attention cells (Equations (A21), (A31), and (A33)) were numerically integrated until equilibrium using a second-and-third order Runge-Kutta formula with adaptive integration step size (Matlab function ode23). Equilibrium for the latter stages was defined as the sum-of-squares activity not changing by more than 0.25% for three successive integration steps for each model stage. The boundary and surface attention stages constitute feedback signals that influence the initial stages of the model and thus the entire processing hierarchy. Therefore, once these stages reached equilibrium, their activities were sampled and incorporated into the two stages that directly receive them: Boundary attention derived from the bipolar cells in Equation (A21) influences the LGN (Equation (A4)), and surface-based attention from the PPC (Equation A33) influences the V1 layer 6 simple cells (Equation (A10)). After incorporating feedback signals into the early stages, the entire dARTEX hierarchy was re-calculated and the numerical integration of the three stages...
mentioned above was performed again, leading to the next equilibrium state. Model outputs did not change perceivably after three such iterations of equilibration and re-calculation. All results shown are after three iterations, except the images in Figure 4b and 4e that denote activity before the feedback kicks in. These figures were sampled at equilibrium just before the first re-calculation of dARTEX stages.

In what follows, each dARTEX processing stage is described in order of its activation in response to bottom-up retinal input.

A1 Center-Surround Field, LGN. The LGN stage consists of a spatial competitive stage with on-center, off-surround filters (ON channel) as well as off-center, on-surround filters (OFF channel). This stage discounts the illuminant and normalizes image contrast. As seen in Figure 1, in addition to bottom-up retinal input, the LGN stage also receives top-down modulatory boundary-based attention.

The activity \( x_{ijs}^+ \) of the LGN ON channel neuron at spatial position \((i,j)\) and scale \(s\) obeys a shunting on-center, off-surround equation:

\[
\dot{x}_{ijs}^+ = -\alpha_x x_{ijs}^+ + \left(1 - x_{ijs}^+\right) \left[I_{ij} (1 + \lambda_x f_{ij})\right] - \left(1 + x_{ijs}^+\right) \left[\sum_{pq} I_{pq} (1 + \lambda_x f_{pq}) G_{pqij\sigma_s(s)}\right]. \tag{A4}
\]

In (A4), the term \(\alpha_x x_{ijs}^+\) on the right hand side defines a passive decay at rate \(\alpha_x = 0.25\). In the excitatory term \((1 - x_{ijs}^+)[I_{ij} (1 + \lambda_x f_{ij})]\), retinal input \(I_{ij}\) at position \((i,j)\) is gain-modulated by a boundary-based attentional signal \(f_{ij}\) defined in Equation (A30). The signal \(f_{ij}\) amplifies LGN activity at figure boundaries. The inhibitory term \((1 + x_{ijs}^+)[\sum_{pq} I_{pq} (1 + \lambda_x f_{pq}) G_{pqij\sigma_s(s)}]\) suppresses the neighborhood around the boundaries through an inhibitory surround. In Equation (A4), the top-down gain factor \(\lambda_x = 25\), and the Gaussian surround kernel \(G_{pqij\sigma_s(s)}\) in the inhibitory term is defined in Equation (A3), with scale-dependent variances \(\sigma_x(s) = [4.5, 9.0, 13.5]\) determining the extent of surround inhibition for each of the three successively increasing spatial scales.

The equilibrium solution for Equation (A4) is:

\[
x_{ijs}^+ = \frac{(1 + \lambda_x f_{ij}) I_{ij} - \sum_{pq} (1 + \lambda_x f_{pq}) I_{pq} G_{pqij\sigma_s(s)}}{\alpha_x + (1 + \lambda_x f_{ij}) I_{ij} + \sum_{pq} (1 + \lambda_x f_{pq}) I_{pq} G_{pqij\sigma_s(s)}}. \tag{A5}
\]

The LGN OFF channel activities, denoted by \(\bar{x}_{ijs}^-\), are defined as \(\bar{x}_{ijs}^- = -x_{ijs}^+\). They are the activities of an analogous shunting off-center, on-surround equation. This formulation for the model’s simplified LGN stage is adapted from Gove et al. (1995). In some treatments, OFF cells are tonically active in the absence of inputs (e.g., Grossberg et al., 1995). This property was not needed in the present simulations.

A2 Oriented Simple Cells, VI Layers 6 and 4. Two sets of oriented multiple-scale simple cells are simulated in layers 4 and 6 of V1, respectively. As seen in Figure 1, both sets of simple cells are driven by bottom-up activation from the LGN. The simple cells act as polarity-of-contrast sensitive filters that detect oriented features in the image along the filter’s preferred orientation. In model simulations, 24 different simple cell orientations are used for each of the 3 spatial scales. The simple cells in layer 6 are identical to layer 4 simple cells in terms of their bottom-up inputs, but they are also modulated by top-down spatial attention. The spatial attention stage is described in Section A8.

V1 layer 4 simple cells are bottom-up activated by LGN ON and OFF activities sampled through spatially elongated and offset Gaussian kernels. In particular, layer 4 simple cell \(p_{ijks}\) at position \((i,j)\), ori-
factor, and scale \( s \) obeys the equation:

\[
\dot{p}_{ijks} = -\alpha_p p_{ijks} + (1 - p_{ijks}) \sum_{pq} \left( [x^+_{pq}]^+ R_{pqijks}^+ \sigma_p(s) + [x^-_{pq}]^- R_{pqijks}^-(s) \right) \\
- (1 + p_{ijks}) \sum_{pq} \left( [x^+_{pq}]^+ R_{pqijks}^-(s) + [x^-_{pq}]^- R_{pqijks}^+(s) \right).
\]  

(A6)

In (A6), the passive decay rate \( \alpha_p = 0.25 \). In the (A6) excitatory term, LGN ON cell output signals \([x^+_{ij}s]^+\) are filtered by oriented spatially elongated Gaussian kernel \( R_{pqijks}^+(s) \), while the LGN OFF cell output signals \([x^-_{ij}s]^+\) are filtered by a similar kernel \( R_{pqijks}^-(s) \). The centers of the kernels \( R_{pqijks}^+(s) \) and \( R_{pqijks}^-(s) \) are offset in mutually opposite directions from each simple cell’s centroid along an axis perpendicular to the simple cell’s direction of elongated sampling. In the inhibitory term of Equation (A6), the same kernels sample an LGN channel complimentary to the one in the excitatory term. The net activity of simple cells is thus a measure of image feature contrast in its preferred orientation. In mathematical terms, the vertically oriented kernels \( R_{pqijks}^+(s) \) and \( R_{pqijks}^-(s) \) in (A6) are:

\[
R_{pqijks}^\pm(s) = A_p(s) \exp \left( -\frac{(i - p \pm \sigma_p(s)/2)^2 + (j - q)^2}{2\sigma_p^2(s)} \right),
\]  

(A7)

where superscripts + and − denote positive and negative lobes of the kernel that are centered at \((i \pm \sigma_p(s)/2, j)\), respectively. Each kernel has a scale-dependent spatial variance \( \sigma_p(s) = [1, 2, 3] \) along its narrow axis that determines the spatial region over which average contrast is measured, and an elongation factor \( \delta = 2 \) for the long axis. Other lobe orientations are generated by coordinate system rotation. The normalization factor \( A_p(s) = (2\pi\sigma_p^2(s)\delta)^{-1} \) in Equation A7 ensures that kernel lobes individually add to 1.

The equilibrium solution of simple cell activity of Equation (A6) equals:

\[
p_{ijks} = \frac{A - B}{\alpha_p + A + B},
\]  

(A8)

where the terms \( A \) and \( B \) are:

\[
A = \sum_{pq} \left( [x^+_{pq}]^+ R_{pqijks}^+ + [x^-_{pq}]^- R_{pqijks}^-(s) \right) \\
B = \sum_{pq} \left( [x^+_{pq}]^+ R_{pqijks}^- + [x^-_{pq}]^- R_{pqijks}^+(s) \right).
\]  

(A9)

By (A8), the simple cell equilibrium activity detects luminance contrast in the preferred orientation, indeed contrast-normalizes its responses according to a Weber law (Grossberg, 1980). The magnitude of the Weber law parameter, or, equivalently, the passive decay rate \( \alpha_p \), determines how quickly contrast normalization sets in as input activities increase. In dARTEX simulations, \( \alpha_p \) is chosen to achieve a balance of high contrast normalization and sensitivity to top-down attentional modulation.

Symmetric sampling of LGN ON and OFF channel activities by simple cells in Equation (A6) ensures that a simple cell encoding a light-to-dark edge in a given orientation has the same activity as another simple cell of complementary contrast polarity preference when it responds identical dark-to-light edge. This balance in activation is important for processing form boundaries independent of their luminance contrast polarity. The simple cell Equations (A6) and (A8) are adapted from Ross et al. (2000).

V1 layer 6 simple cells have receptive fields identical to those of layer 4 simple cells. Additionally, layer 6 simple cells are modulated by top-down spatial attention; see Equation (A33). In the initial feedforward
phase of input activation, when spatial attention is not yet active, simple cells in layers 4 and 6 exhibit identical responses. However, as spatial attention activates, it suppresses unattended layer 6 simple cells through surround inhibition from nearby attended locations. Specifically, layer 6 simple cell activity $a_{ijks}$ at position $(i, j)$, orientation $k$, and scale $s$ obeys the equation:

$$
\dot{a}_{ijks} = -\alpha_a a_{ijks} + (1 - a_{ijks}) \left(1 + \Theta(r_{ij})\right) \frac{1}{p} \sum_{pq} \left(\left[x_{pq}^+ R_{pqijks}^+(s)\delta + x_{pq}^- R_{pqijks}^-(s)\delta\right]\right)
- \left(1 + a_{ijks}\right) \left(1 + \sum_{mn} \Theta(r_{mn})G_{mnijsa(s)}(s)\right) \left(\sum_{pq} \left[x_{pq}^+ R_{pqijks}^+(s)\delta + x_{pq}^- R_{pqijks}^-(s)\delta\right]\right).$$

(A10)

In (A10), the passive decay rate $\alpha_a = 0.25$. The on-center and off-surround terms in Equation (A10) that sample LGN activity $[x_{pq}]^\pm$ using simple cell kernel lobes $R_{pqijks}^\pm(s)\delta$ are the same as Equation (A6). The on-center is top-down attentively amplified through the modulatory term $(1 + \Theta(r_{ij}))$. The signal $\Theta(r_{ij})$ in this term is input from spatial attention $r_{ij}$ in Equation (A33). Through a similar modulatory term in the off-surround, $(1 + \sum_{mn} \Theta(r_{mn})G_{mnijsa(s)}(s))$, unattended cells around the locus of spatial attention are strongly inhibited.

The attentional signal function $\Theta(r_{ij})$ in Equation (A10) normalizes all above-threshold spatial attention activities $r_{ij}$ to approximately the same signal size. Specifically,

$$
\Theta(r_{ij}) = \frac{\lambda_a (r_{ij} - \gamma_a)^+}{\epsilon_a + (r_{ij} - \gamma_a)^+},
$$

(A11)

where $\lambda_a = 2$, $\gamma_a = 0.05$, and the Weber law parameter $\epsilon_a = 0.05$. A large gain $\lambda_a$ and a small Weber law parameter $\epsilon_a$ ensure that unattended simple cells surrounding the attended ones are strongly inhibited through the term $(1 + \sum_{mn} \Theta(r_{mn})G_{mnijsa(s)}(s))$ in Equation (A10), while simple cell activity at attended locations is uniformly amplified. This attentional modulation in Equation (A10) prevents mixing of dART input features across texture boundaries during local texture classification and learning, improving overall model performance. This property of dARTEx is described in Section 2.9. The Gaussian kernel $G_{pqijsa(s)}$ in Equation (A16) is defined in Equation (A3) with scale-dependent variance $\sigma_a(s) = [4.5, 9, 13.5]$ and determines the spatial extent of attentive inhibition of unattended features.

The equilibrium solution of V1 layer 6 simple cell activity in Equation (A10) obeys

$$
a_{ijks} = \frac{A - B + (A\Theta(r_{ij}) - B \sum_{mn} \Theta(r_{mn})G_{mnijsa(s)})}{\alpha_p + A - B + (A\Theta(r_{ij}) + B \sum_{mn} \Theta(r_{mn})G_{pqijsa(s)})},
$$

(A12)

where the terms $A$ and $B$ are defined in Equation (A9). The equilibrium solution in Equation (A12) shows that layer 6 activity is identical to layer 4 activity in absence of attention (when $\Theta(r_{pq}) = 0$, for all $p$ and $q$); see Equation (A8). When spatial attention activates, the term $B \sum_{mn} \Theta(r_{mn})G_{mnijsa(s)}$ in the numerator of Equation (A12) ensures that unattended simple cells in the surround (where $\Theta(r_{pq})$ is close to 1) are inhibited.

As seen in Figure 1, V1 layer 6 simple cells activate a distributed learned category representation in the dART network (Carpenter, 1997). This category representation reads-out learned expected simple cell activities at each image location; see Equation (A35). The layer 4 simple cell activity is matched with this learned expectation via the layer 6 to 4 modulatory network (Callaway, 1998; Grossberg & Raizada, 2000). Specifically, match activity $m_{ijks}$ for position $(i, j)$, orientation $k$, and spatial scale $s$ is (Carpenter, 1997):

$$
m_{ijks} = 0.5 \left[\min \left(\sigma_{ijks}, [p_{ijks}]^+\right) + 1 - \min \left(\sigma_{ijks}^-, 1 - [p_{ijks}]^+\right)\right],
$$

(A13)
where $\sigma_{ijks}$ is the dART expected ON simple cell activity, and $\sigma_{ijks}^c$ is the expected OFF simple cell activity. This complementarity of ON and OFF features will be described as part of the definition of the dART input feature vector in Equation (A34). The feature expectation term $\sigma_{ijks}$ is defined in Equation (A35). Simple cell signals $[p_{ijks}]^+$ from V1 layer 4 are defined in Equation (A6). By Equation (A13), the match signal is an average of matched activities of the ON and OFF simple cell activities. This matching operation facilitates dARTEX processing by reducing feature noise, and thereby facilitates the completion of object form boundaries, as described in Section 2.9. The matched features in Equation (A13) are the bottom-up inputs to complex cells of V1 layer 2/3.

A3 Complex Cells, V1 Layer 2/3. Each complex cell receives activity from pairs of simple cells that are selective to opposite contrast polarities, and thereby acts as an oriented polarity-of-contrast insensitive filter. The complex cell activity $q_{ijks}$ for position $(i,j)$, orientation $k$, and scale $s$ obeys the equation:

$$q_{ijks} = [m_{ijks}]^+ + [m_{ijKs}]^+,$$

(A14)

where $m_{ijks}$ is the matched simple cell activity described in Equation (A13). The orientation index $K$ in Equation (A14) denotes the matched simple cell of contrast polarity opposite to the one indexed by $k$. Since there are 24 simple cell orientations, the above operation produces 12 unique orientations of complex cells for each spatial scale. The complex cell activities are adapted from Gove et al. (1995). However, there was no dART matching of simple cell activities in that work.

A4 Spatial and Orientational Competition, V2 Layers 6 and 4. As seen in Figure 1, the two competitive stages in V2 are driven by complex cell activities arriving from V1 layer 2/3. The spatial competition stage activity $u_{ijks}$ at position $(i,j)$, orientation $k$, and scale $s$ obeys the equation:

$$\dot{u}_{ijks} = -\alpha_u u_{ijks} + (1 - u_{ijks}) (J + q_{ijks}) - (1 + u_{ijks}) \left( \sum_{pqr} q_{pqr} K_{pqrijksu(s)\omega_u} \right),$$

(A15)

where the passive decay rate $\alpha_u = 0.25$, $J = 0.01$ is a constant tonic activity, and $q_{ijks}$ is the complex cell activity arriving from V1 layers 2/3 as defined in Equation (A14). The spatial competition kernel $K_{pqrijksu(s)\omega_u}$ in Equation (A15) is a product of two Gaussian kernels, one that depends on orientation, and the other that depends on spatial distance. In particular, kernel $K_{pqrijksu(s)\omega_u}$ at position $(i,j)$ and orientation $k$ is:

$$K_{pqrijksu(s)\omega_u} = A_u(s) \exp \left( -\frac{(\min(r-k,O - r + k))^2}{2\omega_u^2} \right) G_{pqijksu(s)},$$

(A16)

The first Gaussian kernel in (A16) is the orientation kernel: it is maximal for the orientation $k$ with a Gaussian fall-off for more dissimilar orientations, $O = 12$ is the total number of complex cell orientations, and the orientation-dependent Gaussian drop-off variance $\omega_u = 0.43$. The second spatial Gaussian kernel in (A16) is defined in Equation (A3) with a scale-dependent variance $\sigma_u(s) = [4.5, 9, 13.5]$. Thus, in Equation (A15), similar orientations in a local image neighborhood inhibit each other the most. Coefficient $A_u(s) = ((2\pi)^{1/2}\omega_u)^{-1}$ in Equation (A16) is a scale-dependent normalization factor such that the kernel adds to 1.

As a result of spatial competition between like-oriented complex cell outputs in Equation (A15), uniform activity in luminance and orientation is suppressed, while discontinuities in their spatial distribution are
enhanced. The equilibrium solution of the spatial competition stage in Equation (A15) is:

$$u_{ijks} = \frac{J + q_{pqrs} - \sum_{pq} q_{pqrs} K_{pqrijk\sigma_{v}(s)}\omega_{v}}{\alpha_{v} + J + q_{pqrs} + \sum_{pq} q_{pqrs} K_{pqrijk\sigma_{v}(s)}\omega_{v}}.$$  \hspace{1cm} (A17)

As seen in Figure 1, the orientational competition stage in V2 is driven by the outcome of the spatial competition. At this stage, mutually orthogonal orientations inhibit each other the most. Factor \(\lambda_{v}\) is defined in Equation (A3) with a scale-dependent variance \(\omega_{v}\).

The equilibrium solution of the spatial competition stage in Equation (A15) is:

$$\dot{v}_{ijks} = \alpha_{v} v_{ijks} + (1 - v_{ijks}) \left( [u_{ijks} - \gamma_{v}]^{+} \right) - (1 + v_{ijks}) \left( \sum_{pq} [u_{pqrs} - \gamma_{v}]^{+} L_{pqrijk\sigma_{v}(s)}\omega_{v} \right),$$  \hspace{1cm} (A18)

where the passive decay rate \(\alpha_{v} = 0.05\). Signal \([u_{ijks} - \gamma_{v}]^{+}\) is the input from the spatial competition stage defined in Equation (A15), with output threshold \(\gamma_{v} = 0.005\). The orientational competition kernel is a product of two Gaussian kernels, one that depends on orientation, and the other that depends on spatial distance. In particular, kernel \(L_{pqrijk\sigma_{v}(s)}\omega_{v}\) centered at position \((i, j)\) and orientation \(k\) is:

$$L_{pqrijk\sigma_{v}(s)}\omega_{v} = A_{v}(s)\exp \left( -\frac{(O/2 - \min(r - k, O - r + k))^{2}}{2\omega_{v}^{2}} \right) G_{pqrijk\sigma_{v}(s)},$$  \hspace{1cm} (A19)

where the first, orientation Gaussian kernel is maximal for an orientation perpendicular to the orientation \(k\) with a Gaussian fall-off for more similar orientations, \(O = 12\) is the total number of complex cell orientations, and the orientation-dependent Gaussian drop-off variance \(\omega_{v} = 0.84\). The second spatial Gaussian kernel in (A19) is defined in Equation (A3) with a scale-dependent variance \(\sigma_{v}(s) = [1, 2, 3]\). Thus, in Equation (A18), dissimilar orientations in a local image neighborhood inhibit each other the most. Factor \(A_{v}(s) = ((2\pi)^{1/2}\omega_{v})^{-1}\) in Equation (A19) is a scale-dependent normalization factor such that the kernel adds to 1. The equilibrium solution for the orientational competitive stage defined in Equation (A18) is:

$$v_{ijks} = \frac{[u_{ijks} - \gamma_{v}]^{+} - \sum_{pq} [u_{pqrs} - \gamma_{v}]^{+} L_{pqrijk\sigma_{v}(s)}\omega_{v}}{\alpha_{v} + [u_{ijks} - \gamma_{v}]^{+} + \sum_{pq} [u_{pqrs} - \gamma_{v}]^{+} L_{pqrijk\sigma_{v}(s)}\omega_{v}}.$$  \hspace{1cm} (A20)

The two competitive stages defined in Equations (A15) and (A18) were introduced into the neural modeling of boundary grouping in Grossberg (1984) and are adapted from Grossberg & Mingolla (1985a, 1985b).

A5 Bipole Grouping Cells, V2 Layer 2/3. The bipole grouping stage in layer 2/3 of V2 is driven by competitive stage output from layer 4 of V2, as seen in Figure 1. Bipole cells receive long-range monosynaptic excitatory inputs from other bipole cells and short-range disynaptic inhibitory connections from a shared pool of interneurons. Specifically, bipole cell activity \(z_{ijks}\) at position \((i, j)\), orientation \(k\), and scale \(s\) obeys the equation:

$$\dot{z}_{ijks} = -z_{ijks} + (1 - z_{ijks}) \left( \lambda_{z} [v_{ijks} - \gamma_{z1}]^{+} + \beta_{z} [h_{ijks}^{L} - \gamma_{z2}]^{+} + \beta_{z} [h_{ijks}^{R} - \gamma_{z2}]^{+} \right)$$

$$- (1 + z_{ijks}) (m_{ijks} + g_{ijks}^{L} + g_{ijks}^{R}),$$  \hspace{1cm} (A21)

where \(\lambda_{z} [v_{ijks} - \gamma_{z1}]^{+}\) is the bottom-up excitatory input signal from the orientational competition stage defined in Equation (A18) with gain \(\lambda_{z} = 1\) and output threshold \(\gamma_{z1} = 0.005\). Long-range horizontal
excitatory signals $\beta_z [h_{ijks}^{L/R} - \gamma z]^{+}$ are received from bipole cells on the two coaxial flanks (denoted by L and R) of each bipole cell, with gain $\beta_z = 7.5$ and output threshold $\gamma z = 0.005$. The signals $[h_{ijks} - \gamma z]^{+}$ are defined in Equation (A22). The spatial and orientational competition term $m_{ijks}$ in Equation (A21) receives signals from other bipole cells as defined in Equation (A28). The di-synaptic inhibition terms $g_{ijks}^{L/R}$ in Equation (A21) realize the bipole property as defined in Equation (A29).

In what follows, the horizontal bipole orientation is assumed for the sake of notational simplicity. Other bipole orientations are derived by co-ordinate system rotation.

The long-range horizontal excitatory kernels $h_{ijks}^{L/R}$ in Equation (A21) obey:

$$h_{ijks}^{L/R} = \sum_{pqr} [z_{pqrs} - \gamma z]^{+} H_{pqrijkl\sigma_z(s)\omega_z(s)\psi_z(s)}^{L/R},$$

which sum output signals $[z_{ijks} - \gamma z]^{+}$ from bipole cells defined in Equation (A21) with output threshold $\gamma z = 0.005$. The left half-kernel $H_{pqrijkl\sigma_z(s)\omega_z(s)\psi_z(s)}^{L}$ is a product of three Gaussian kernels which determines the amount of sampling from other bipole cells based on their distance, lateral offset from the horizontal axis, and deviation from the preferred orientation at various locations in the receptive field. As a result, proximal, coaxially located, and co-aligned bipole cells are sampled with higher weight. Specifically, the left half-kernel $H_{pqrijkl\sigma_z(s)\omega_z(s)\psi_z(s)}^{L}$ at position $(i, j)$, orientation $k$, and scale $s$ is:

$$H_{pqrijkl\sigma_z(s)\omega_z(s)\psi_z(s)}^{L} = \begin{cases} \mathcal{A}_H(s) \exp \left( -\frac{(p-i)^2 + (q-j)^2}{2\sigma_z(s)^2} \right) \exp \left( -\frac{K_{pqij}^2}{2\omega_z^2} \right) \exp \left( -\frac{\left(\frac{2\pi}{\omega_z^2}\right)^2}{2\psi_z^2} \right) & \text{if } i < 0 \\ 0 & \text{otherwise} \end{cases}$$

(A23)

The first term

$$\exp \left( -\frac{(p-i)^2 + (q-j)^2}{2\sigma_z(s)^2} \right),$$

in (A23) is an isotropic spatial Gaussian with scale-dependent variance $\sigma_z(s) = [100, 200, 300]$. This term controls the spatial extent of the bipole half-kernel, with larger scales performing boundary groupings over a longer spatial range. The second term in Equation (A23),

$$\exp \left( -\frac{K_{pqij}^2}{2\omega_z^2} \right),$$

(A25)

determines contributions from locations lateral to the horizontal axis of the kernel: Term $K_{pqij}$ ensures that farther and more laterally offset locations contribute less. Drop-off of the kernel with distance and thickness is governed by parameter $\omega_z = 0.001$. A larger value of $\omega_z$ results in a kernel with a thicker band around the principal axis. The factor $K_{pqij}$ in equation (A25) for a bipole cell at position $(i, j)$ is:

$$K_{pqij} = \arctan \left( \frac{(p-i)(q-j)}{(p-i)^2 - (q-j)^2} \right).$$

(A26)

Factor $K_{pqij}$ above is sensitive to both the distance between locations $(i, j)$ and $(p, q)$ and the spatial offset of position $(p, q)$ from the horizontal axis. For example, along the principal axis $q = j$, $K_{pqij} = 0$, and the term in Equation (A25) is at its maximum of 1. As position $(p, q)$ departs the principal axis, and moves farther from position $(i, j)$, $K_{pqij}$ diverges to infinity. In this case, Equation (A23) vanishes in the limit.
determines the contribution from other bipole cells based on their orientation \( r \) and position \((p, q)\). This term is sensitive to three attributes: Orientation of the contributing bipole cell \( r \), its offset from the horizontal axis, \((q - j)\), and its distance from the position \((i, j)\) of target bipole cell receiving the input. Through this term, contributions from the same bipole orientation are maximal along the principal axis. Contributions from dissimilar bipole orientations increase while those from similar bipole orientations decrease as offset from the principal axis increases. By controlling the amount of pooling from dissimilar orientations, the term in Equation (A27) limits the maximum curvature of the boundaries that can be completed. In particular, parameter \( \psi_z = 0.0001 \) in Equation (A27) controls the highest curvature that can be grouped. A larger value of \( \psi_z \) enables grouping of more dissimilar orientations, and thereby grouping of boundaries with higher curvatures. The constant \( O = 12 \) in the above equation denotes the total number of orientations. Finally, coefficient \( A_H(s) = 0.5((2\pi)^2\sigma_z^2(s)\omega_z\psi_z)^{-1} \) in Equation (A23) normalizes the kernel to add to 0.5.

The spatial and orientational competition term \( m_{ijks} \) in Equation (A21) sharpens boundaries and reduces orientational ambiguity. For position \((i, j)\), orientation \( k \), and scale \( s \), term \( m_{ijks} \) is:

\[
m_{ijks} = A_m \sum_{pqr} [z_{pqrs} - \gamma_m]^+ L_{pqrijk}(s)\omega_m, \tag{A28}
\]

where the constant \( A_m = 2.5 \) is a gain factor, terms \([z_{pqrs} - \gamma_m]^+ \) in Equation (A28) are output signals from bipole cells defined in Equation (A21) with \( \gamma_m = 0.005 \), and the orientational competition kernel \( L_{pqrijk}(s)\omega_m \) is defined in Equation (A19) with \( \omega_m = 2.5 \) and scale-dependent spatial variance \( \sigma_m(s) = [1, 2, 3] \).

The left \((L)\) and right \((R)\) interneuron activity \( g^{L/R}_{ijks} \) at position \((i, j)\), orientation \( k \), and scale \( s \) in Equation (A21) is:

\[
g^{L/R}_{ijks} = D_g \left(-g^{L/R}_{ijks} + \lambda_g [h^{L/R}_{ijks} - \gamma_g]^+ - C_g g^{L/R}_{ijks} [g^{R/L}_{ijks}]^+ \right), \tag{A29}
\]

where the gain \( D_g = 50 \) makes the inhibitory interneuron settling time more rapid than that of the bipole cell. Excitatory signal \( \lambda_g [h^{L/R}_{ijks} - \gamma_g]^+ \) comes from bipole cells defined in Equation (A22), with gain \( \lambda_g = 7.5 \) and output threshold \( \gamma_g = 0.005 \). The left and the right interneurons mutually inhibit each other with inhibition gain \( C_g = 7.5 \).

As seen in the inhibitory term of Equation (A29), the left and the right interneurons provide mutual shunting inhibition. Therefore, excitation of the two interneurons from their associated bipole flanks results in shunting normalization of the interneurons activates and thus normalization of the total inhibitory interneuron input to the bipole cell; see Equation (A21). This normalization of total inhibition from the interneurons allows the bipole cell to fire strongly even in the absence of direct bottom-up input. On the other hand, in the absence of bottom-up input to the bipole cell, and when only one of the two interneurons receives excitation from its associated bipole flank, equal amounts of excitation through direct horizontal input to the bipole and inhibition from the interneuron prevents the bipole cell from firing. This mechanism prevents an outward spread of activity while enabling inward oriented completion of boundaries. The
present formulation of the bipole cell-network is adapted from Ross et al. (2000) and from Grossberg & Swaminathan (2004).

A6 Boundary-Based Attention, From V2 to LGN. As seen in Figure 1, boundary-based attention is derived by summing the bipole activities in V2 layers 2/3 over all orientations and scales. This modulatory boundary-based attention signal (Gove et al., 1995) amplifies LGN activity at grouped boundaries while suppressing their neighborhood by acting on the LGN surround kernels. The pooling across all scales ensures that features at the boundaries are eventually amplified in every spatial scale even when some scales are initially unsuccessful at detecting object boundaries. The LGN activity is defined in Equation (A4). The boundary-based attention signal $f_{ij}$ at position $(i,j)$ and scale $s$ is defined as:

$$\dot{f}_{ij} = -\alpha f_{ij} + \sum_{ks} [z_{ijks} - \gamma f]^{+},$$

(A30)

where passive decay rate $\alpha_f = 1$, and $[z_{ijks} - \gamma f]^{+}$ is the input from the bipole cells defined in Equation (A21), with $\gamma_f = 0.005$.

A7 Surface Filling-In Domain, V4. Bipole signals added over all orientations and scales define a long-range figural boundary contour. If the boundary is a closed contour, the boundary-gated featural filling-in process can define a figural surface (Grossberg, 1994; Grossberg & Howe, 2003; Grossberg & Todorović, 1988). Surface filling-in activity $h_{ij}s$ at position $(i,j)$ and scale $s$ obeys a boundary-gated diffusion equation:

$$\dot{h}_{ij}s = -h_{ij}s + \left[ x_{ij}^{+} \right]^{+} + \beta_{h} \varphi \left( [r_{ij}]^{+} \right) + \sum_{pq\in N(ij)} (h_{ij}s - h_{pq}s) P_{pqij}s,$$

(A31)

where $x_{ij}^{+}$ is the LGN ON channel activity defined in Equation (A4), $\beta_{h} = 3$, $r_{ij}$ is the spatial attentional signal defined in Equation (A33), signal function $\varphi(x) = \frac{x}{1 + x}$, and the diffusion permeability $P_{pqij}s$ is defined in Equation (A32). $N(ij)$ in Equation (A31) is the set of eight nearest-neighbor cells adjacent to the cell at position $(i,j)$ with which the $(i,j)$ cell directly interacts during filling-in. The permeability $P_{pqij}s$ that gates the diffusion process in Equation (A31) is defined by the equation:

$$P_{pqij}s = \frac{\lambda_{P}}{\alpha_{P} + \sum_{k} \left( [z_{pqks}]^{+} + [z_{ijks}]^{+} \right)},$$

(A32)

with diffusion gain factor $\lambda_{P} = 21 \times 10^{6}$, Weber law parameter $\alpha_{P} = 3.3 \times 10^{-5}$, and $z_{ijks}$ is the bipole activity defined in Equation (A21).

A8 Spatial Attention, PPC. Figure 1 shows connectivity of the spatial attention stage, which generates a form-fitting attentional shroud in response to feedback with the surface filling-in domain. In particular, this stage receives as bottom-up activation the surface filling-in domain output from V4, as well as a spatially localized top-down volitional attention signal. Specifically, spatial attention activity $r_{ij}$ at position $(i,j)$ is defined by the equation:

$$\dot{r}_{ij} = -\alpha_{r} r_{ij} + \left( 1 - r_{ij} \right) \left( \sum_{pq} [\lambda_{r} \varphi (\sum_{s} h_{pq}s) + \beta_{r} I_{pq}] G_{pqij} \sigma_{r} \right) - \left( 1 + r_{ij} \right) \left[ \sum_{pq} \lambda_{r} \varphi (\sum_{s} h_{pq}s) G_{pqij} \sigma_{r2} \right],$$

(A33)

where passive decay rate $\alpha_{r} = 1$. Bottom-up input signal $\varphi(h_{pq}s)$ is from the surface filling-in domain in Equation (A31) with signal function $\varphi(x) = x/(1 + x)$ and gain factor $\lambda_{r} = 100$. Term $I_{pq}$ is the volitional top-down attentional signal, modeled by a $3 \times 3$ pixel wide spot of activity assigned to a location inside
the attended surface, with gain $\beta_r = 2$. The volitional attentional signal $I_{pq}$ locally enhances the spatial attentional activity. Through spatial attentional signal to the filling-in domain, this signal diffuses within the attended surface; see Equation (A31). The spread of volitional attention in the surface filling-in domain in turn enhances the activity of the entire attended form in Equation (A33) through bottom-up inputs. As the attended shroud grows due to volitional attention, other weaker shrouds are suppressed in Equation (A33) by long range spatial competition. A volitionally selected, form-filling spatial attentional shroud is thus formed in this stage. Gaussian kernels $G_{pqij\sigma_{11}}$ and $G_{pqij\sigma_{12}}$ in Equation (A33) are defined in Equation (A3), with variances $\sigma_{r1} = 3$ and $\sigma_{r2} = 40$, respectively.

**A9 dART-Based Texture Learning, Classification, and Top-Down Attentive Matching.** Input to the dART network is a vector that combines spatially pooled layer 6 ON simple cell signals $a_{ijks}$ defined in Equation (A10), and OFF simple cell signals $1 - a_{ijks}$. These ON and OFF cell signals normalize to pairwise add to 1. In ART, this preprocessing stage is called complement coding (Carpenter et al., 1991b). Complement coding ensures that the input feature vector of length $2M$ adds to a constant $M$. Specifically, the complement-coded dART input feature vector $A_{ij}$ at position $(i, j)$ is:

$$A_{ij} = \left[ \sum_{pq} [a_{pq11}]^+ G_{pqij\sigma_A(s)} + \sum_{pq} [a_{pq21}]^+ G_{pqij\sigma_A(s)} + \cdots + \sum_{pq} [a_{ijKS}]^+ G_{pqij\sigma_A(s)}, \right.$$

$$\left. 1 - \sum_{pq} [a_{pq11}]^+ G_{pqij\sigma_A(s)}, 1 - \sum_{pq} [a_{pq21}]^+ G_{pqij\sigma_A(s)}, \cdots, 1 - \sum_{pq} [a_{ijKS}]^+ G_{pqij\sigma_A(s)} \right],$$

(A34)

where $[a_{ijks}]^+$ are output signals from V1 layer 6 simple cells defined in Equation (A10) and the Gaussian kernel $G_{pqij\sigma_A(s)}$ is defined in Equation (A3), with spatial scale dependent variance $\sigma_A(s) = [1, 2, 3]$. In Equation (A34), $K = 24$ is the number of simple cell orientations, and $S = 3$ is the number of scales. The dART input is thus a 144 dimensional complement-coded feature vector.

The importance of spatial pooling of simple cells in texture classification was investigated by Grossberg & Williamson (1999), where they observed that larger spatial pooling extents resulted in better texture classification, but also caused classification errors at texture boundaries due to feature mixing. In dARTEX, the detrimental effect of feature mixing at texture boundaries is circumvented through spatial attentional modulation of dART inputs, as described in Equation (A10).

Section B2 describes how the dART network responds to complement coded input vectors. In response to this bottom-up input, the dART network reads out top-down learned expectations of simple cell activities, which are described next.

The dART top-down simple cell expectation $\sigma_{ijks}$ at position $(i, j)$, orientation $k$, and scale $s$ is (Carpenter, 1997):

$$\sigma_{ijks} = \sum_{n=1,...,N} [y_{nij} - \tau_{nks}]^+, \quad (A35)$$

where the summation is over all $N$ categories in the dART network. In the dART network, $y_{nij}$ is the $n$th category cell activity at position $(i, j)$ defined in Equations (B10) and (B11). Learned feature threshold $\tau_{nks} = 1 - w_{nks}$ in Equation (A35) is derived from the $n$th dART category weight $w_{nks}$ for orientation $k$ and scale $s$; also see Section B1, Step 2.

**A10 Texture Boundary Contrast Measure for the OBTS Task Simulation.** The texture boundary salience measure $S$ for comparing simulation results to the psychophysical data of Ben-Shahar & Zucker (2004) is
defined by the equation:

\[ S = \mu \frac{E_{\text{Lower}} - E_{\text{Upper}}}{\nu + E_{\text{Lower}} + E_{\text{Upper}} + F + 50}, \]  
(A36)

where \( \mu = 67 \) and \( \nu = 0.13 \). The pooled boundary activities at the two possible locations of the horizontal discontinuity figure boundaries \( E_{\text{Lower/Upper}} \) are defined in Equation (A37). The factor \( F \) is the average bipole activity over the whole image, defined in Equation (A40). The above equation arises from a shunting on-center, off-surround network (Grossberg, 1973, 1980) that detects pooled boundary contrast at two possible figure boundary locations. The term \( F \) in Equation (A36) normalizes the measure and requires that, in order to be salient, the attended boundary contrast must be stronger than the average boundary activity in the scene. For dARTEX simulations, the horizontal boundary was always located at the lower location. Therefore, any increase in the measure in Equation (A36) denotes an increased detection accuracy.

The boundary activity \( E_{\text{Lower/Upper}} \) in Equation (A36) is derived by pooling the bipole activities using a product of two kernels. The first kernel determines the spatial region of pooling, while the second determines the relative weights applied to each boundary orientation during pooling. Specifically, the pooled boundary activity at the \( E_{\text{Lower/Upper}} \) is defined as:

\[ E_{\text{Lower/Upper}} = \sum_{ijks} [z_{ijks} - \gamma E]^+ D_{ijks}^{L}\text{ower/Upper} O_{kR}, \]  
(A37)

where \([z_{ijks} - \gamma E]^+\) is the output signal from the bipole cell in Equation (A21) with \( \gamma E = 0.005 \). The spatial pooling kernel \( D_{ijks}^{\text{Lower/Upper}} \) is a horizontal band centered at the either the lower or the upper possible boundary location, respectively, and defined in Equation (A38). The second term, \( O_{kR} \), defined in Equation (A39), is the orientational pooling kernel that determines the weights of different orientations during pooling.

The spatial pooling kernel \( D_{ijks}^{\text{Lower/Upper}} \) is horizontally elongated over the whole image and is centered at a possible boundary location (either Lower or Upper) with a Gaussian fall-off in the vertical direction. Specifically, the spatial pooling kernel \( D_{ijks}^{\text{Lower/Upper}} \) at vertical image position \( j \) is:

\[ D_{ijks}^{\text{Lower/Upper}} = \frac{1}{98 \sqrt{2\pi \sigma_D}} \exp \left( -\frac{(j - q_{\text{Lower/Upper}})^2}{2\sigma_D^2} \right), \]  
(A38)

where variance \( \sigma_D = 15 \). The vertical center of this kernel is either at the lower boundary location (mean = \( q_{\text{Lower}} \)) or at the upper boundary location (mean = \( q_{\text{Upper}} \)). The orientation pooling kernel \( O_{kR} \) in Equation (A39) is either a uniform normalized kernel for all \( k \), or a Gaussian centered at orientation \( R \):

\[ O_{kR} = \frac{1}{\sqrt{2\pi \omega_O}} \exp \left( -\frac{(k - R)^2}{2\omega_O^2} \right), \]  
(A39)

where variance \( \omega_O = 3.175 \). Parameter \( R \) is chosen to be the horizontal orientation, being the maximally active orientation at the attended boundary locations. Term \( F \) in Equation (A36) adds all bipole output signals:

\[ F = A_F \sum_{ijks} [z_{ijks} - \gamma E]^+, \]  
(A40)

where coefficient \( A_F = 2.3 \times 10^{-6} \), \( z_{ijks} \) is the bipole activity described in Equation (A21), and the output
threshold $\gamma_E = 0.005$. The term $F$ penalizes the salience measure in Equation (A36) whenever average boundary activity in the scene is high.

B Default ARTMAP Implementation

The default ARTMAP algorithm (Carpenter, 2003) implements the dART network in the dARTEX model presented here. It is a special case of the distributed ART algorithm described in Carpenter (1997). In the default ARTMAP implementation, supervised training occurs in a Winner-Take-All (WTA) mode where the maximally active category that realizes a feature matching criterion is updated (Carpenter et al., 1992). Testing activates a distributed category code and the predicted class label is determined through a weighted vote.

In the following description, operator $|.|$ denotes the $L_1$ norm of its vector argument, and operator $\wedge$ denotes the fuzzy intersection operation; that is, a component-wise minimum of the two vector arguments in the operator. All vector arguments are denoted by bold-face type.

The untrained ARTMAP network begins with a pool of $N$ uncommitted category cells that are not bound to any class label. As learning progresses, cells from this pool are recruited, or committed, to encode prescribed sets of input feature patterns. The population of committed category nodes grows with learning, and its size ($C$) is determined by learning task demands. For a complete description of how this occurs in the distributed ART framework, see Carpenter (1997). Description of the default ARTMAP in this section is limited to essential implementation details. For further implementation information, see Carpenter (1997) and Carpenter et al. (1998).

B1 Default ARTMAP Training. During training, default ARTMAP learns to associate an $M$ dimensional feature vector $\mathbf{a}$ to a supplied class label. The training algorithm is described by the following steps:

1. For all positions $(i,j)$ to be learned, generate complement coded input feature vectors $\mathbf{A}_{ij}$ defined in Equation (A34).

2. Set initial values: Set the initial feature-to-category weight $w_{ksn} = 1$ from input feature of orientation $k$ and scale $s$ to category $n$. Also set the initial category-to-feature weight $w_{nks} = 1$ from category $n$ to input cell of orientation $k$ and scale $s$. Set initial class weights $W_{nm} = 1$ from each category $n$ to each class label $m$. Set number of committed category nodes $C = 1$. For the Winner-Take-All (WTA) mode of learning utilized here, the bottom-up feature-to-category weights $w_{ksn}$ and the top-down category-to-feature weights $w_{nks}$ remain identical (Carpenter, 1997). Both these weight vectors for category $n$ are therefore denoted by $w_n$.

3. Select the first input vector in the dataset, $\mathbf{A}_{ij}$, at position $(i,j)$, with associated output class $K$.

4. Set initial weights for the newly committed category node $n = C$, where $C = 1$ is the latest committed category node index:

$$w_C = \mathbf{A}_{ij}, \quad (B1)$$

and set the the class weight from the category node $C$ to output class $K$:

$$W_{Ck} = \begin{cases} 
1 & \text{if } k = K \\
0 & \text{if } k \neq K 
\end{cases} \quad (B2)$$

5. Set vigilance $\rho$ to its baseline value $\bar{\rho} = 0.6$:

$$\rho = \bar{\rho}, \quad (B3)$$
and reset the code at position \((i, j)\):

\[ y_{ij} = 0. \]  \hspace{1cm} (B4)

6. Select input vector \(A_{ij}\) at the next position \((i, j)\), with associated actual output class \(K\) (until the last input of the last training epoch).

7. At position \((i, j)\), calculate signals \(T_{nij}\) to committed category nodes \(n = 1, \ldots, C\) using the choice-by-difference signal function (Carpenter & Gjaja, 1994):

\[ T_{nij} = |A_{ij} \land w_n| + (1 - \alpha)(M - |w_n|), \]  \hspace{1cm} (B5)

where \(w_n\) is the weight vector for category \(n\). Note that for an uncommitted node \(|w_n| = 2M\), so \(T_{nij} = \alpha M\). Small values of the signal rule parameter \(\alpha\) cause the system to select category nodes that would minimize learned changes in \(w_n\) during learning. For present simulations, \(\alpha = 0.075\).

8. Search order: Search the committed categories with \(T_{nij} > \alpha M\) in order of \(T_{nij}\) values (max to min) for position \((i, j)\).

9. Search for a category \(R\) that meets the matching criterion and predicts the correct output class \(K\), as follows:

(a) Code: For the next category node \(R\) that meets the matching criterion

\[ \left( \frac{|A_{ij} \land w_R|}{M} > \rho \right), \text{ set } y_{Rij} = 1 \text{ (winner-take-all)} \]  \hspace{1cm} (B6)

(b) Output class prediction: With category \(n\), position \((i, j)\), and class \(m\), the class prediction

\[ \psi_{mij} = \sum_{n=1}^{C} W_{nm} y_{nij} = W_{Rm}. \]

(c) Correct prediction: If the active code \(R\) predicts the actual output class \(K\), that is, \(\psi_{Kij} = W_{RK} = 1\), then go to Step 11 (learning).

(d) Match tracking: If the active node \(R\) fails to predict the correct output class \(\psi_{Kij} = 0\), raise vigilance to:

\[ \rho = \frac{|A_{ij} \land w_R|}{M} + \varepsilon, \]  \hspace{1cm} (B7)

where the match tracking parameter \(\varepsilon = -0.0001\) (MT-, Carpenter & Markuzon, 1998). Return to Step 9(a) (continue search).

10. After unsuccessfully searching the sorted list, increase \(C\) by 1 (add a committed category). Return to Step 4.

11. Learning: Update the feature-to-category weights as follows:

\[ w^\text{new}_R = \beta |A_{ij} \land w^\text{old}_R| + (1 - \beta)w^\text{old}_R, \]  \hspace{1cm} (B8)

where \(\beta = 1\) is the learning fraction for fast learning. \(A_{ij}\) is the input feature vector for the current position \((i, j)\) defined in Equation (A34), and \(w^\text{old}_R\) is the category node weight vector prior to learning.

$B2$ Default ARTMAP Testing (Distributed Code)

1. For all positions $(i, j)$ to be classified, generate complement coded input feature vectors $A_{ij}$ defined in Equation (A34).

2. Select input vector $A_{ij}$ at the next position $(i, j)$.

3. Reset the category code at position $(i, j)$: $y_{ij} = 0$.

4. Calculate input signals $T_{nij}$ to all categories $n$ at position $(i, j)$ according to the choice-by-difference signal function (Carpenter & Gjaja, 1994):

$$n = 1, \ldots, C : T_{nij} = |A_{ij} \land w_n| + (1 - \alpha) (M - |w_n|).$$

(B9)

During testing, the signal rule parameter $\alpha$ is set to 0.075, same as during training. Recall that the signal $T_{nij}$ to each uncommitted node $n$ is the constant $\alpha M$.

5. $\Lambda$ is the set of indices of categories firing above threshold, and $\Lambda'$ is the set of indices of categories exactly matching the input. In particular, $\Lambda = \{\lambda = 1, \ldots, C : T_{\lambda ij} > \alpha M\}$ and $\Lambda' = \{\lambda = 1, \ldots, C : T_{\lambda ij} = M\} = \{\lambda = 1, \ldots, C : w_\lambda = A_{ij}\}$.

6. Increased Gradient (IG) CAM Rule: A Content Addressable Memory (CAM) rule specifies a function that characterizes the steady-state activity of the short term memory in response to a given vector of inputs converging on a field of neurons. The Increased Gradient (IG) CAM rule used here contrast-enhances the input differences as represented in the distributed category code (Carpenter, 1997; Carpenter et al., 1998).

(a) Point box case occurs when at least one category exactly encodes the input and the set $\Lambda'$ is not empty. In this case, only such categories are activated: If $\Lambda'$ is not empty (i.e., $w_n = A_{ij}$ for some $n$), set

$$y_{nij} = \frac{1}{|\Lambda'|} \text{ for each } n \in \Lambda'.$$

(B10)

(b) In cases other than a point box case, when $\Lambda$ is not empty, a distributed category activation of coding neurons is realized with the best matching categories activating the most:

$$y_{nij} = \left[\frac{1}{M - T_{nij}}\right]^p \sum_{\lambda \in \Lambda} \left[\frac{1}{M - T_{\lambda ij}}\right]^p$$

(B11)

for each $n \in \Lambda$,

where $T_{nij}$ is the input signal to category $n$ at position $(i, j)$, defined in Equation (B9). In Equation (B11), power law parameter $p = 5$ determines the amount of code contrast enhancement. As $p$ increases, the category activation increasingly resembles a winner-take-all code in which only the category with highest bottom-up signal survives (Carpenter, 1997). Constant $M$ in Equation (B11) is the number of input features to dART.

7. Calculate distributed output class predictions for position $(i, j)$:

$$\psi_{mij} = \sum_{n=1}^C W_{nm} y_{nij}.$$  

(B12)
8. Predict output classes from $\psi_{mij}$ values for position $(i, j)$:

$$K_{ij} = \arg \max_m \psi_{mij}. \quad (B13)$$

9. While there are more test inputs, return to Step 2.
References


