Texture perception

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As we parse the retinal image into different objects, a number of visual properties are used to distinguish figure from ground and one object from neighboring objects. These properties include luminance, color, relative motion, and stereo disparity. Within a single surface there can be variation in surface reflectance, color, or three-dimensional orientation (surface roughness). These variations result in a textured retinal image. These textural variations can be regular (textiles, brick walls, honeycomb), random (forest floor), or in between (wood grain).

The occurrence of texture in a scene is useful in a number of ways. (1) The characteristics of a single texture may be used to identify the surface material as in knowing the type of wood from the grain (*texture appearance*). (2) When two objects (or parts of a single object) meet, an edge is formed. Identifying and localizing edges is a basic step in the figure-ground problem, and edges can involve a change in texture (alone or in conjunction with a change of other surface properties). Thus, *texture segregation* can be an important component in identifying objects. (3) When a textured object is viewed, the geometry of perspective results in a distortion of the texture in the retinal image. Characteristics of the texture in the image may be used to infer properties of the three-dimensional layout of objects and object shape (*shape from texture*). All of these capabilities have been studied both psychophysically and computationally, and there have been recent advances in understanding the neurophysiological basis for texture perception.

The area that has seen the greatest amount of effort has been in understanding the mechanisms of texture segregation. A considerable amount of research involves the use of synthetic textures involving texture elements (e.g. dots, line segments, small figures such as *Ls*, *Ts*, and *Xs*) that are placed on a uniform background in either a regular or a random fashion. Other work has used continuous-tone textures such as sums of sinusoids or filtered noise. The use of randomly placed texture elements was developed by (Julesz 1981; Caelli and Julesz, 1978). An example of a result of this work is illustrated in Figure 1. Here, a region of randomly placed *Xs* is easily distinguished from a background of *Ls*. However, a foreground region of *Ts* can only be distinguished with scrutiny. There is no visible texture edge or perceived textured object on a background even though the individual texture elements are easily discriminable.

The work of Julesz and colleagues led to a number of different theoretical positions on which pairs of textures will segregate easily. Their early work led to the conjecture that observers were sensitive only to differences in the first- and second-order statistics of constituent textures. However, counterexamples to this conjecture have been found. Difficulties with this entire line of reasoning have been pointed out recently by Yellott (1993), as the statistics to be compared were not those of the presented texture patterns, but rather of the ensembles from which they were drawn (because iso-third-order images are, in fact, identical images). The appearance of these counterexamples led Julesz to an entirely different, feature-based theoretical approach. The basic features or *textons* are defined as required by the empirical results, and include elongated blobs and line endings or terminators. Texture segregation was proposed to result from differences in the characteristics of the blobs (number, length, orientation, etc.) and number of terminators in the constituent textures.

A number of investigators (e.g., Bergen and Adelson, 1988; Caelli, 1993; Graham, Beck, and Sutter, 1992; Landy and Bergen, 1991; Malik and Perona, 1990) have recently proposed computational models of texture segregation with a common form: a set of linear spatial filters similar in form to cortical simple cells, a point-wise nonlinearity, and further linear spatial filtering (which can result in responses similar to those of cortical complex cells). These models convert a difference in texture into a difference in response magnitude, allowing the texture edge to be enhanced and detected by conventional edge detection methods. The form of the models is inspired by neurophysiology. It has become a standard model in vision science that has unified the study of texture with other areas of spatial vision. Similar models have been applied to visual motion analysis as well. Because the models are implemented as computer algorithms, they may be applied to both pen-and-ink textures of the sort used by Julesz as well as continuous-tone and natural textures. They have been successful at modeling a variety of texture segregation phenomena such as the effects of texture element shape, size, and spacing (Figure 2).

A number of different issues have been important in the recent texture literature. First, there are a number of different tasks that can be used to evaluate the perception of texture. At the same time that Julesz was studying texture segregation with images of randomly placed texture elements, Treisman and Gelade (1980) looked at the ability of observers to find a single element (a target) on a background of varying numbers of other texture elements (distractors). There are a number of similarities in the results of texture segregation, visual search, and other paradigms (e.g., texture-defined object discrimination) using identical texture element pairs. But it is not always true that texture element pairs lead to easy search if and only if they lead to good texture segregation (Wolfe, 1992). Even with a fixed pair of texture elements, there are often asymmetries in performance (Gurnsey and Browse, 1989), depending on which element is the target (or composes the foreground texture) and which is the distractor (or background). In addition, the type of texture elements used is only one component of good performance on texture segregation tasks. The placement of the texture elements (at random, or in a set pattern) is also important, leading some researchers (e.g. Beck, 1982) to concentrate on properties that lead to perceptual grouping of texture elements.

We have concentrated on a review of perceptual texture segregation research, but texture is useful for other purposes and has been studied in other communities. The distortion of projected texture with changes in viewing geometry is a cue to surface geometry as discussed, for example, by Gibson (1950). It has been noted that perception of shape from surface texture is a response to several cues including changes in texture element density, size, and shape. In computer vision, texture segregation (for object recognition), texture appearance (e.g., for identification of land usage in satellite photographs), and shape from texture have been studied extensively. In neurophysiology there has been a great deal of interest in relating the luminance edge responses of neurons (especially in cortical areas V1 and V2) to their responses to texture-defined edges (and other "illusory contours"). Recently, this has been related to neural responses to stimulation outside of the traditional receptive field.

1. See also

Stereopsis, binocular perception
Visual cortex, extrastriate
Visual perception
Figure-ground separation by visual cortex

Author's website:
http://www.cns.nyu.edu/~msl/

2. Further Reading

Beck J, Prazdny K, Rosenfeld A (1983): A theory of textural segmentation. In: *Human and Machine Vision*, Beck J, Hope B, Rosenfeld A, eds. New York: Academic Press, pp. 1-38

Bergen JR (1991): Theories of visual texture perception. In: *Vision and Visual Dysfunctio*n, Volume 10B, Regan D, ed. New York: Macmillan, pp. 114-134

Cutting JE, Millard RT (1984): Three gradients and the perception of flat and curved surfaces*. J Exp Psychol Gen* 113:198-216 [MEDLINE]

Lamme VAF (1995): The neurophysiology of figure-ground segregation in primary visual cortex. *J Neurosci* 15:1605-1615 [MEDLINE]

Landy MS, Graham N (2004): Visual perception of texture. In: *The Visual Neurosciences*, Chalupa LM, Werner JS, eds. Cambridge, MA: MIT Press, pp. 1106-1118

Malik J, Rosenholtz R (1994): A computational model for shape from texture. In: *Higher-order Processing in the Visual System*, Bock GR, Goode JA, eds. Ciba Foundation Symposium, 184; Chichester, England: Wiley, pp. 272-286 [MEDLINE]

Nothdurft HC (1985): Sensitivity for structure gradient in texture discrimination tasks. *Vision Res* 25:1957-1968 [MEDLINE]

Rubenstein BS, Sagi D (1990): Spatial variability as a limiting factor in texture-discrimination tasks: implications for performance asymmetries. *J Optical Soc Am A* 7:1632-1643 [MEDLINE]

Todd JT, Akerstrom RA (1987): Perception of three-dimensional form from patterns of optical texture. *J Exp Psychol Hum Percept Perform* 13:242-255 [MEDLINE]

3. Additional Material

In this section a reference list is provided of recent papers on texture perception, sorted by topic.

3.1. Reviews

Here are a couple of reviews of texture perception, as well as an empirical paper that discusses the relationship between texture segregation and pop out.

Bergen JR (1991): Theories of visual texture perception. In: *Vision and Visual Dysfunction*, Vol 10B, Regan D, ed. New York: Macmillan, pp. 114-134

Landy MS, Graham N (2004): Visual perception of texture. In: *The Visual Neurosciences*, Chalupa LM, Werner JS, eds. Cambridge, MA: MIT Press, pp. 1106-1118

Wolfe JM (1992): "Effortless" texture segmentation and "parallel" visual search are not the same thing. *Vision Res* 32:757-763 [MEDLINE]

3. 2. Texture segmentation

Here is a broad selection of papers that concern texture segmentation performance, computational models of texture segmentation, as well as a number of papers that do not involve texture segmentation tasks per se, but are still intended to elucidate the structure of early, second-order texture processing.

Arsenault AS, Wilkinson F, Kingdom FAA (1999): Modulation frequency and orientation tuning of second-order texture mechanisms. *J Optical Soc Am A* 16:427-435 [MEDLINE]

Beck J (1972): Similarity grouping and peripheral discriminability under uncertainty. *Am J Psychol* 85:1-19 [MEDLINE]

Beck J (1973): Similarity grouping of curves. *Percept Motor Skill* 36:1331-1341 [MEDLINE]

Beck J (1982): Textural segmentation. In: *Organization and Representation in Perception*, Beck J, ed. Hillsdale, NJ: Erlbaum, pp. 285-317

Beck J, Prazdny K, Rosenfeld A (1983): A theory of textural segmentation. In: *Human and Machine Vision*, Beck J, Hope B, Rosenfeld, A, eds. New York: Academic Press, pp. 1-38

Bergen JR, Adelson EH (1988): Early vision and texture perception. *Nature* 333:363-364 [MEDLINE]

Bergen JR, Julesz B (1983): Parallel versus serial processing in rapid pattern discrimination. *Nature* 303:696-698 [MEDLINE]

Bergen JR, Landy MS (1991): Computational modeling of visual texture segregation. In: *Computational Models of Visual Processing*, Landy MS, Movshon JA, eds. Cambridge, MA: MIT Press, pp. 253-271

Bovik AC, Clark M, Geisler WS (1990): Multichannel texture analysis using localized spatial filters. *IEEE T Pattern Anal* 12:55-73

Braun J, Sagi D (1990): Vision outside the focus of attention. *Percept Psychophys* 48:45-58 [MEDLINE]

Caelli T (1985): Three processing characteristics of visual texture segmentation. *Spatial Vision* 1:19-30 [MEDLINE]

Caelli T (1993): Texture classification and segmentation algorithms in man and machines. *Spatial Vision* 7:277-292 [MEDLINE]

Caelli T, Julesz B (1978): On perceptual analyzers underlying visual texture discrimination: part I. *Biol Cybern* 28:167-175 [MEDLINE]

Caelli T, Julesz B, Gilbert EN (1978): On perceptual analyzers underlying visual texture discrimination: part II. *Biol Cybern* 29:201-214 [MEDLINE]

Chubb C, Econopouly J, Landy MS (1994): Histogram contrast analysis and the visual segregation of IID textures. *J Optical Soc Am A* 11:2350- 2374 [MEDLINE]

Chubb C, Landy MS (1991): Orthogonal distribution analysis: a new approach to the study of texture perception. In: *Computational Models of Visual Processing*, Landy MS, Movshon JA, eds. Cambridge, MA: MIT Press, pp. 291-301

Dakin SC, Mareschal I (2000): Sensitivity to contrast modulation depends on carrier spatial frequency and orientation. *Vision Res* 40:311-329 [MEDLINE]

Dakin SC, Williams CB, Hess RF (1999): The interaction of first- and second-order cues to orientation. *Vision Res* 39:2867-2884 [MEDLINE]

Fogel I, Sagi D (1989): Gabor filters as texture discriminator. *Biol Cybern* 61:103-113

Graham N (1991): Complex channels, early local nonlinearities, and normalization in perceived texture segregation. In: *Computational Models of Visual Processing, Landy MS,* Movshon JA, eds. Cambridge, MA: MIT Press, pp. 291-301

Graham N (1992): Breaking the visual stimulus into parts. *Curr Dir Psychol Sci* 1:55-61

Graham N, Beck J, Sutter A (1992): Nonlinear processes in spatial-frequency channel models of perceived texture segregation: effects of sign and amount of contrast. *Vision Res* 32:719-743 [MEDLINE]

Graham N, Sutter A (1998): Spatial summation in simple (Fourier) and complex (non-Fourier) texture channels. *Vision Res* 38:231-257 [MEDLINE]

Graham N, Sutter A (2000): Normalization: contrast-gain control in simple (Fourier) and complex (non-Fourier) pathways of pattern vision. *Vision Res* 40:2737-2761 [MEDLINE]

Graham N, Sutter A, Venkatesan C (1993): Spatial-frequency- and orientation-selectivity of simple and complex channels in region segmentation. *Vision Res* 33:1893-1911

Graham N, Wolfson SS (2001): A note about preferred orientations at the first and second stages of complex (second-order) texture channels. *J Optical Soc Am A* 18:2273-2281 [MEDLINE]

Gurnsey R, Browse RA (1989): Asymmetries in visual texture discrimination. *Spatial Vision* 4:31-44 [MEDLINE]

He ZJ, Nakayama K (1994): Perceiving textures: beyond filtering. *Vision Res* 34:151-162 [MEDLINE]

Joseph JS, Chun MM, Nakayama K (1997): Attentional requirements in a 'preattentive' feature search task. *Nature* 387:805-807 [MEDLINE]

Julesz B (1981): Textons, the elements of texture perception, and their interactions. *Nature* 290:91-97 [MEDLINE]

Julesz B, Gilbert EN, Shepp LA, Frisch HL (1973): Inability of humans to discriminate between visual textures that agree in second-order statistics revisited. *Perception* 2:391-405 [MEDLINE]

Julesz B, Gilbert EN, Victor JD (1978): Visual discrimination of textures with identical third-order statistics. *Biol Cybern* 31:137-140 [MEDLINE]

Kehrer L (1989): Central performance drop on perceptual segregation tasks. *Spatial Vision* 4:45-62 [MEDLINE]

Kingdom FAA, Hayes A, Field DJ (2001): Sensitivity to contrast histogram differences in synthetic wavelet-textures. *Vision Res* 41:585-598 [MEDLINE]

Kingdom FAA, Keeble DRT (1996): A linear systems approach to the detection of both abrupt and smooth spatial variations in orientation-defined textures. *Vision Res* 36:409-420 [MEDLINE]

Kingdom FAA, Keeble DRT (1999): On the mechanism for scale invariance in orientation-defined textures. *Vision Res* 39:1477-1489 [MEDLINE]

Kingdom FAA, Keeble DRT, Moulden B (1995): Sensitivity to orientation modulation in micropattern-based textures. *Vision Res* 35:79-91 [MEDLINE]

Knutsson H, Granlund GH (1983): Texture analysis using two-dimensional quadrature filters. Proceedings of the IEEE Computer Society Workshop on Computer Architecture for Pattern Analysis and Image Database Management. Silver Spring, MD: *IEEE Computer Society*, pp. 206-213

Landy MS, Bergen JR (1991): Texture segregation and orientation gradient. *Vision Res* 31:679-691 [MEDLINE]

Landy MS, Kojima H (2001): Ideal cue combination for localizing texture-defined edges. *J Optical Soc Am A* 18:2307-2320 [MEDLINE]

Lee TS (1995): A Bayesian framework for understanding texture segmentation in the primary visual cortex. *Vision Res* 35:2643-2657 [MEDLINE]

Lin LM, Wilson HR (1996): Fourier and non-Fourier pattern discrimination compared. *Vision Res* 36:1907-1918 [MEDLINE]

Malik J, Perona P (1990): Preattentive texture discrimination with early vision mechanisms. *J Optical Soc Am A* 7:923-932 [MEDLINE]

Motoyoshi I (1999): Texture filling-in and texture segregation revealed by transient masking. *Vision Res* 39:1285-1291 [MEDLINE]

Motoyoshi I, Nishida S (2001): Temporal resolution of orientation-based texture segregation. *Vision Res* 41:2089-2105 [MEDLINE]

Mussap AJ (2001): Orientation integration in detection and discrimination of contrast- modulated patterns. *Vision Res* 41:295-311 [MEDLINE]

Nothdurft HC (1985): Sensitivity for structure gradient in texture discrimination tasks. *Vision Res* 25:1957-1968 [MEDLINE]

Olson RK, Attneave F (1970): What variables produce similarity grouping? *Am J Psychol* 83:1-21

Papathomas TV, Gorea A, Feher A, Conway TE (1999): Attention-based texture segregation. *Percept Psychophys* 61:1399-1410 [MEDLINE]

Rivest J, Cavanagh P (1996): Localizing contours defined by more than one attribute. *Vision Res* 36:53-66 [MEDLINE]

Rubenstein BS, Sagi D (1990): Spatial variability as a limiting factor in texture- discrimination tasks: implications for performance asymmetries. *J Optical Soc Am A* 7:1623-1643

Schofield AJ, Georgeson MA (1999): Sensitivity to modulations of luminance and contrast in visual white noise: separate mechanisms with similar behavior. *Vision Res* 39:2697-2716 [MEDLINE]

Schofield AJ, Georgeson MA (2000): The temporal properties of first- and second-order vision. *Vision Res* 40:2475-2487 [MEDLINE]

Sutter A, Beck J, Graham N (1989): Contrast and spatial variables in texture segregation: testing a simple spatial-frequency channels model. *Percept Psychophys* 46:312-332 [MEDLINE]

Sutter A, Graham N (1995): Investigating simple and complex mechanisms in texture segregation using the speed-accuracy tradeoff method. *Vision Res* 35:2825-2843 [MEDLINE]

Sutter A, Hwang D (1999): A comparison of the dynamics of simple (Fourier) and complex (non-Fourier) mechanisms in texture segregation. *Vision Res* 39:1943-1962 [MEDLINE]

Sutter A, Sperling G, Chubb C (1995): Measuring the spatial frequency selectivity of second-order texture mechanisms. *Vision Res* 35:915-924 [MEDLINE]

Turner MR (1986): Texture discrimination by Gabor functions. *Biol Cybern* 55:71-82 [MEDLINE]

Victor JD (1988): Models for preattentive texture discrimination: Fourier analysis and local feature processing in a unified framework. *Spatial Vision* 3:263-280 [MEDLINE]

Wolfson SS, Landy MS (1995): Discrimination of orientation-defined texture edges. *Vision Res* 35:2863-2877 [MEDLINE]

Wolfson SS, Landy MS (1998): Examining edge- and region-based texture mechanisms. *Vision Res* 38:439-446 [MEDLINE]

Wolfson SS, Landy MS (1999): Long range interactions between oriented texture elements. *Vision Res* 39:933-945 [MEDLINE]

Yeshurun Y, Carrasco M (2000): The locus of attentional effects in texture segmentation. *Nat Neurosci* 3:622-627 [MEDLINE]

3. 3. Texture appearance and representation

The following papers are concerned with the parameters needed to model texture appearance, constituting a *representation* for a texture class. The Gibson book is far more general, but includes the notion of surface texture as an indication of physical surface qualities (*affordances*).

Dana KJ, van Ginneken B, Nayar SK, Koenderink JJ (1999): Reflectance and texture of real-world surfaces. *ACM T Graph* 18:1-34

De Bonet JS, Viola P (1998): A non-parametric multi-scale statistical model for natural images. In: *Advances in Neural Information Processing Systems 9*, Jordan MI, Kearns MJ, Solla SA, eds. Cambridge, MA: MIT Press, pp. 773-779

Durgin FH (2001): Texture contrast aftereffects are monocular; texture density aftereffects are binocular. *Vision Res* 41:2619-2630 [MEDLINE]

Gibson JJ (1979): *The Ecological Approach to Visual Perception*. Boston: Houghton-Mifflin

Gurnsey R, Fleet DJ (2001): Texture space. *Vision Res* 41:745-757 [MEDLINE]

Harvey LO, Gervais MJ (1978): Visual texture perception and Fourier analysis. *Percept Psychophys* 24:534-542 [MEDLINE]

Heeger D, Bergen JR (1995): Pyramid-based texture analysis/synthesis. *Proceedings of ACM SIGGRAPH* 1995. New York: Association for Computing Machinery, pp. 229-238

Portilla J, Simoncelli EP (2000): A parametric texture model based on joint statistics of complex wavelet coefficients. *Int J Comput Vision* 40:49- 71

Rao AR, Lohse GL (1996): Towards a texture naming system: identifying relevant dimensions of texture. *Vision Res* 36:1649-1669 [MEDLINE]

Richards W, Polit A (1974): Texture matching. *Kybernetik* 16:155-162 [MEDLINE]

Zhu SC, Wu Y, Mumford D (1998): Filters, random fields and maximum entropy (FRAME): towards a unified theory for texture modeling. *Int J Comput Vision* 27:107-126

3. 4. Physiology

The following papers are concerned with the physiological correlates of texture perception. Some papers attribute texture segmentation to the properties of cells in V1 to have response modulated by visual stimulation outside of the classical receptive field. Others suggest these lateral interaction effects are generally suppressive (e.g., a form of gain control) and have limited relevance for texture segmentation and the computation of figure and ground.

Freeman RD, Ohzawa I, Walker G (2001): Beyond the classical receptive field in the visual cortex. *Prog Brain Res* 134:157-70 [MEDLINE]

Kastner S, de Weerd P, Ungerleider LG (2000): Texture segregation in the human visual cortex: a function MRI study. *J Neurophysiol* 83:2453-2457 [MEDLINE]

Kastner S, Nothdurft HC, Pigarev IN (1997): Neuronal correlates of pop-out in cat striate cortex. *Vision Res* 37:371-376 [MEDLINE]

Kastner S, Nothdurft HC, Pigarev IN (1999): Neuronal responses to orientation and motion contrast in cat striate cortex. *Visual Neurosci* 16:587-600 [MEDLINE]

Knierim JJ, Van Essen DC (1992): Neuronal responses to static texture patterns in area V1 of the alert macaque monkey. *J Neurophysiol* 67:961-980 [MEDLINE]

Lamme VAF (1995): The neurophysiology of figure-ground segregation in primary visual cortex. *J Neurosci* 15:1605-1615 [MEDLINE]

Lennie P (1998): Single units and cortical organization. *Perception* 27:889-935 [MEDLINE]

Levitt JB, Lund JS (1997): Contrast dependence of contextual effects in primate visual cortex. *Nature* 387:73-76 [MEDLINE]

Li Z (2000): Pre-attentive segmentation in the primary visual cortex. *Spatial Vision* 13:25-50 [MEDLINE]

Nothdurft HC, Gallant JL, Van Essen DC (1999): Response modulation by texture surround in primate area V1: correlates of "popout" under anesthesia. *Visual Neurosci* 16:15-34 [MEDLINE]

Nothdurft HC, Gallant JL, Van Essen DC (2000): Response profiles to texture border patterns in area V1. *Visual Neurosc*i 17:421-36 [MEDLINE]

Rossi AF, Desimone R, Ungerleider LG (2001): Contextual modulation in primary visual cortex of macaques. *J Neurosci* 21:1698-1709 [MEDLINE]

Sceniak MP, Hawken MJ, Shapley R (2001): Visual spatial characterization of macaque V1 neurons. *J Neurophysiol* 85:1873-1887 [MEDLINE]

Sillito AM, Grieve KL, Jones HE, Cudeiro J, et al (1995): Visual cortical mechanisms detecting focal orientation discontinuities. *Nature* 378:492-496 [MEDLINE]

Walker GA, Ohzawa I, Freeman RD (2000): Suppression outside the classical cortical receptive field. *Visual Neurosci* 17:369-79 [MEDLINE]

Zipser K, Lamme VAF, Schiller PH (1996): Contextual modulation in primary visual cortex. *J Neurosci* 16:7376-7389 [MEDLINE]

3. 5. Shape from texture

The following papers include behavioral studies and computational models of the inference of three-dimensional shape from texture cues.

Aloimonos J (1988): Shape from texture. *Artif Intell* 38:345-360 [MEDLINE]

Blake A, Buelthoff HH, Sheinberg D (1993): Shape from texture: ideal observers and human psychophysics. *Vision Res* 33:1723-1737 [MEDLINE]

Buckley D, Frisby JP, Blake A (1996): Does the human visual system implement an ideal observer theory of slant from texture? *Vision Res* 36:1163-1176 [MEDLINE]

Cutting JE, Millard RT (1984): Three gradients and the perception of flat and curved surfaces. *J Exp Psychol Gen* 113:198-216 [MEDLINE]

Gibson JJ (1950): *The Perception of the Visual World*. Boston: Houghton-Mifflin

Knill DC (1998): Surface orientation from texture: ideal observers, generic observers and the information content of texture cues. *Vision Res* 38:1655-1682 [MEDLINE]

Knill DC (1998): Discrimination of planar surface slant from texture: human and ideal observers compared. *Vision Res* 38:1683-1711 [MEDLINE]

Knill DC (1998): Ideal observer perturbation analysis reveals human strategies for inferring surface orientation from texture. *Vision Res* 38:2635-2656 [MEDLINE]

Landy MS, Maloney LT, Johnston EB, Young MJ (1995): Measurement and modeling of depth cue combination: in defense of weak fusion. *Vision Res* 35:389-412 [MEDLINE]

Li A, Zaidi Q (2000): Perception of three-dimensional shape from texture is based on patterns of oriented energy. *Vision Res* 40:217-242

[MEDLINE]

Malik J, Rosenholtz R (1994): A computational model for shape from texture. In: *Higher- order Processing in the Visual System*, Bock GR, Goode JA, eds. Ciba Foundation Symposium, 184; Chichester, England: Wiley, pp. 272-286 [MEDLINE]

Malik J, Rosenholtz R (1997): Computing local surface orientation and shape from texture for curved surfaces. *Int J Comput Vision* 23:149-168

Rosenholtz R, Malik J (1997): Surface orientation from texture: isotropy or homogeneity (or both)? *Vision Res* 16:2283-2293

Todd JT, Akerstrom RA (1987): Perception of three-dimensional form from patterns of optical texture. *J Exp Psychol Hum Percept Perform* 13:242-255 [MEDLINE]

Witkin AP (1981): Recovering surface shape and orientation from texture. *Artif Intell* 17:17-45

3. 6. Image statistics

The following papers discuss image gray-level statistics as a potential texture representation.

Chubb C, Yellott JI (2000): Every discrete, finite image is uniquely determined by its dipole histogram. *Vision Res* 40:485-492 [MEDLINE]

Victor JD (1994): Images, statistics, and textures: implications of triple correlation uniqueness for texture statistics and the Julesz conjecture: comment. *J Optical Soc Am A* 11:1680-1684

Yellott JI (1993): Implications of triple correlation uniqueness for texture statistics and the Julesz conjecture. *J Optical Soc Am A* 10:777-793

3.7. Pop out

It has been suggested that the preattentive pop out of a target object from a background of distractor objects in a visual search task has similar characteristics to texture segmentation. Although this is beyond the scope of this review, the following is a small sampling of classic papers in visual search.

Treisman AM (1985): Preattentive processes in vision. *Comput Vision Graph* 31:156-177

Treisman AM, Gelade G (1980): A feature-integration theory of attention. *Cogn Psychol* 12:97-136 [MEDLINE]

Treisman AM, Gormican S (1988): Feature analysis in early vision: evidence from search asymmetries. *Psychol Rev* 95:15-48 [MEDLINE]

Treisman AM, Schmidt H (1982): Illusory conjunctions in the perception of objects. *Cogn Psychol* 14:107-141 [MEDLINE]

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Beck J (1982): Textural segmentation. In: *Organization and Representation in Perception*,

Beck J, ed. *Hillsdale*, NJ: Erlbaum, pp. 285-317

Bergen JR, Adelson EH (1988): Early vision and texture perception. *Nature* 333: 363-364 [MEDLINE]

Caelli T (1993): Texture classification and segmentation algorithms in man and machines. *Spatial Vision* 7:277-292 [MEDLINE]

Caelli T, Julesz B (1978): On perceptual analyzers underlying visual texture discrimination: part I. *Biol Cybern* 28:167-175 [MEDLINE]

Gibson JJ (1950): *The Perception of the Visual World*. Boston, MA: Houghton Mifflin

Graham N, Beck J, Sutter A (1992): Nonlinear processes in spatial-frequency channel models of perceived texture segregation: effects of sign and amount of contrast. *Vision Res* 32:719-743 [MEDLINE]

Gurnsey R, Browse RA (1989): Asymmetries in visual texture discrimination. *Spatial Vision* 4:31-44 [MEDLINE]

Julesz B (1981): Textons, the elements of texture perception, and their interactions. *Nature* 290:91-97 [MEDLINE]

Landy MS, Bergen JR (1991): Texture segregation and orientation gradient. *Vision Res* 31:679-691 [MEDLINE]

Malik J, Perona P (1990): Preattentive texture discrimination with early vision mechanisms. *J Optical Soc Am A* 7:923-932 [MEDLINE]

Treisman AM, Gelade G (1980): A feature-integration theory of attention. *Cogn Psychol* 12:97-136 [MEDLINE]

Wolfe JM (1992): "Effortless" texture segmentation and "parallel" visual search are not the same thing. *Vision Res* 32:757-763 [MEDLINE]

Yellott JI (1993): Implications of triple correlation uniqueness for texture statistics and the Julesz conjecture. *J Optical Soc Am A* 10:777-793

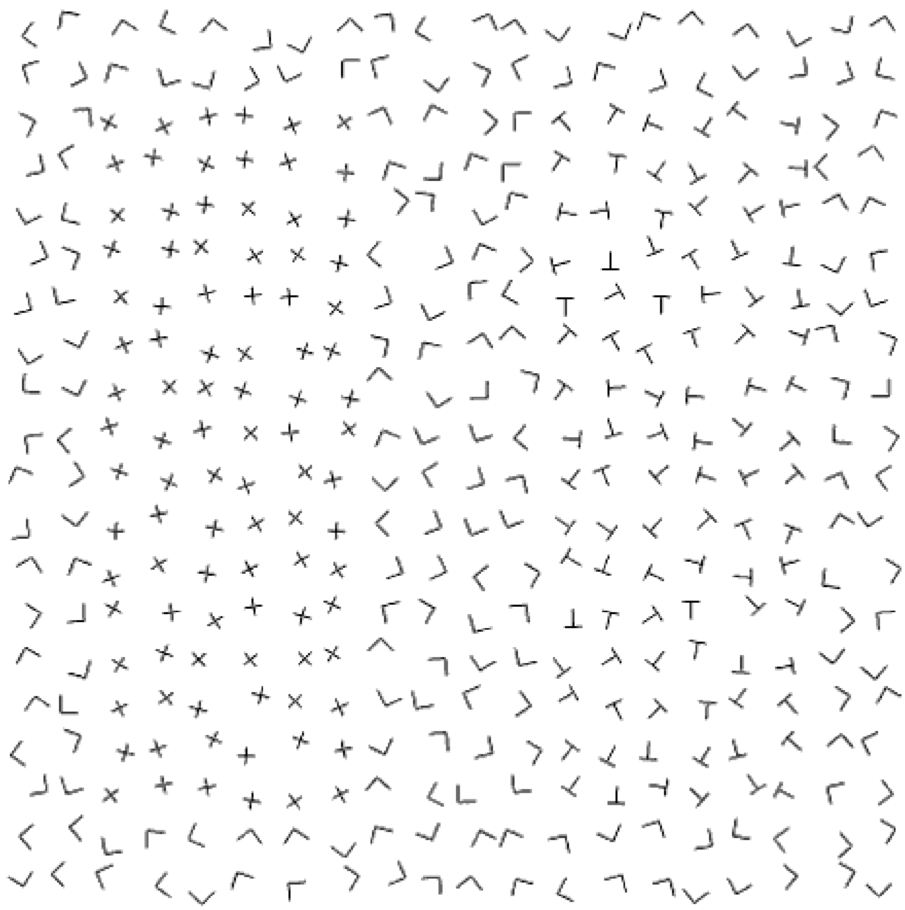

Figure 1. Texture segregation. Notice that the region of *Xs* segregates easily from the background of *Ls*, whereas the region of *Ts* can only be perceived with item-by-item scrutiny.

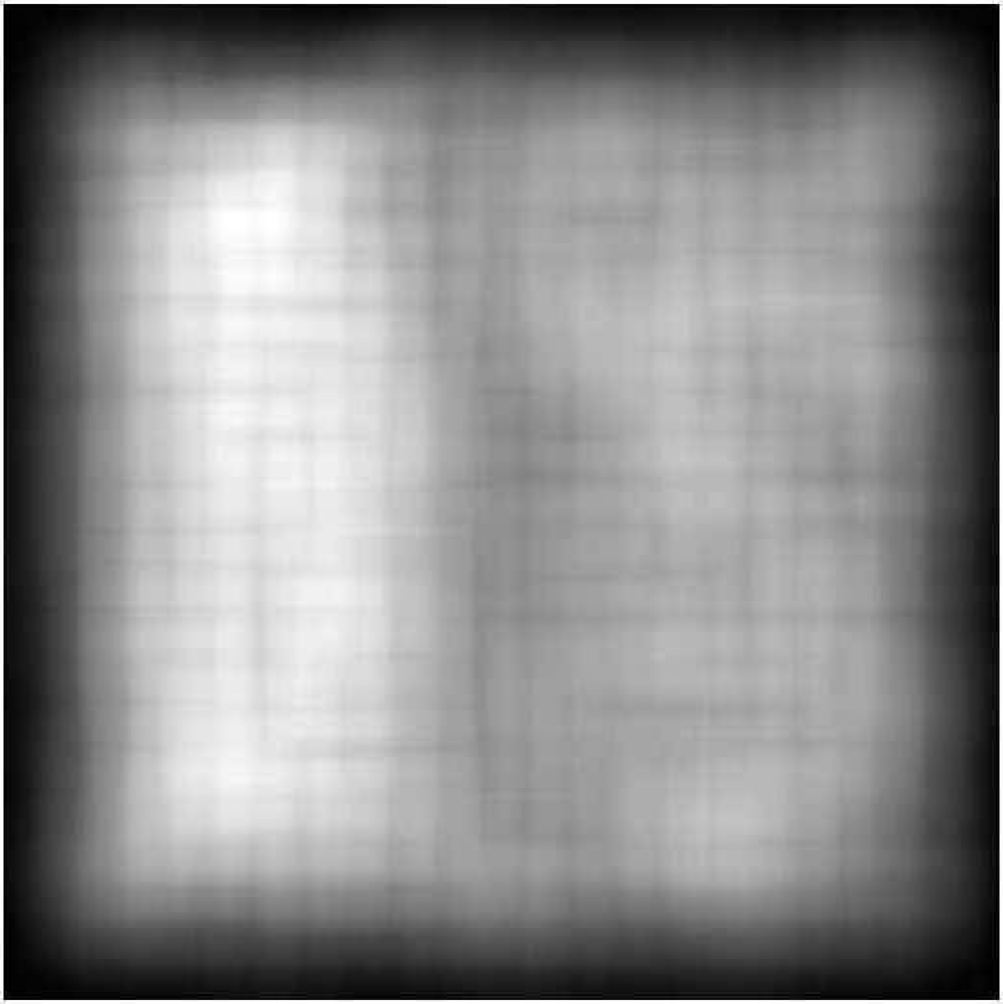

Figure 2. Response of a simple nonlinear filtering model of texture segregation to the stimulus of Figure 1. The stimulus was filtered by an isotropic, bandpass, linear spatial filter (a difference of Gaussians). The resulting image was subjected to a point-wise nonlinearity (x^2), and then blurred. Note how this turns the textural difference that segregates easily into a difference in response strength (Bergen and Adelson, 1988).