

REVIEW ARTICLES

Textons, the elements of texture perception, and their interactions

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Research with texture pairs having identical second-order statistics has revealed that the pre-attentive texture discrimination system cannot globally process third- and higher-order statistics, and that discrimination is the result of a few local conspicuous features, called textons. It seems that only the first-order statistics of these textons have perceptual significance, and the relative phase between textons cannot be perceived without detailed scrutiny by focal attention.

THE study of pre-attentive (also called effortless or instantaneous) texture discrimination can serve as a model system with which to distinguish the role of local texture element detection from global (statistical) computation in visual perception. Indeed, the question of whether there are basic elements in perception out of which higher percepts are built, or whether these higher percepts are indivisible, as the Gestaltist psychologists claimed, is still debated. Without using the sophisticated techniques described in this article, it is not obvious, even in the case of pre-attentive texture discrimination, whether local differences between the texture elements directly contribute to discrimination or whether these differences are sensed in a global way only through differences in the statistics of the texture.

A few examples will clarify this problem. For instance, the texture pair in Fig. 1a effortlessly separates into two distinct textures with a sharp boundary between them. This is true even when the texture pair is presented for 160 ms (or less), outside foveal gaze (to prevent scrutiny of the textures element-by-element by scanning eye movements), and when erasure is used afterwards (to prevent scrutiny of the texture pair's after-image by shifts of focal attention). One 'explanation' of this pre-attentive texture discrimination is that the local texture elements in the two textures which have different sizes are processed by local detectors selectively tuned to different sizes; texture discrimination would be directly conveyed by these detectors. Alternatively, one could describe the difference between the two textures globally, by the difference in their first-order statistics, and assume that this statistical difference underlies

pre-attentive texture discrimination. The first-order statistic (or probability distribution) is simply the probability that randomly thrown dots will land on a certain colour (for example, black) of the texture. This first-order statistic is clearly very different for the two textures in Fig. 1a.

Similarly, the effortless texture discrimination in Fig. 1b can be easily explained by the local orientation difference between the elements that constitute the two textures. But again it is possible to describe the difference between the texture pair globally. Here, the first-order statistics of the two textures are identical, but their second-order statistics differ greatly. The second-order statistic (or joint probability distribution) is the probability of the events that the vertices (end points) of randomly thrown 2gons (dipoles or needles) of all possible lengths and orientations will fall on certain colours of the texture (for example, both on black). [The n gon statistic (or n th order joint probability distribution) of an image can be obtained by randomly throwing n gons of all possible shapes on the image and observing the probabilities that their n vertices fall on certain colour combinations.] Obviously, the second-order (or dipole) statistics are very different for the two textures in Fig. 1b. Finally, Fig. 1c is an example in which the textures are defined globally by keeping their second-order statistics different but their first-order statistics identical, yet the resulting discriminable textures also exhibit locally perceivable differences. Here the left half-image is generated by a two-dimensional Poisson process, while the right-half field is generated by the same process, but with the restriction that no two dots can fall closer to each other than some distance ϵ . A local basis for texture



Fig. 1 Pre-attentively distinguishable texture pairs based either on global statistics or local conspicuous elements, or both: *a*, with different first-order statistics and difference in element size; *b*, with different second-order statistics and different element orientation; *c*, with different second-order statistics that result in short neighbouring dots (dipoles) of critical size that can occur only in one half-field. (From B.J. *et al.*¹⁰.)

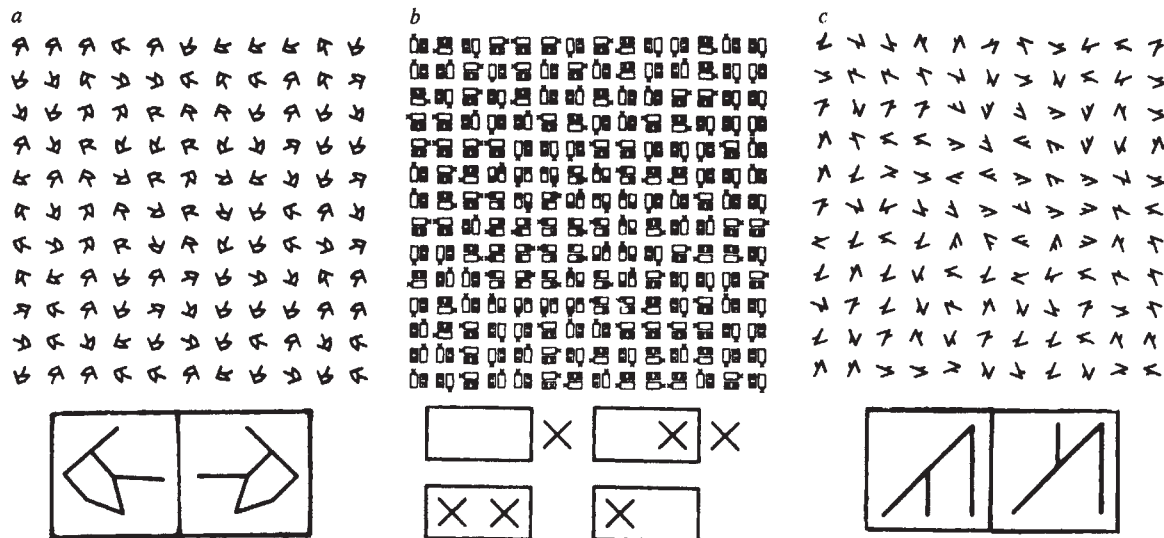


Fig. 2 Pre-attentively indistinguishable texture pairs with identical second-order but different third- and higher-order statistics: *a*, composed of randomly thrown similar micropatterns and their mirror images, respectively (from B.M. *et al.*¹⁰); *b*, composed of dual micropatterns, as described in Fig. 3*b* (from B.J.¹⁶); *c*, composed of dual micropatterns as described in Fig. 3*b* (from B.J.¹⁶).

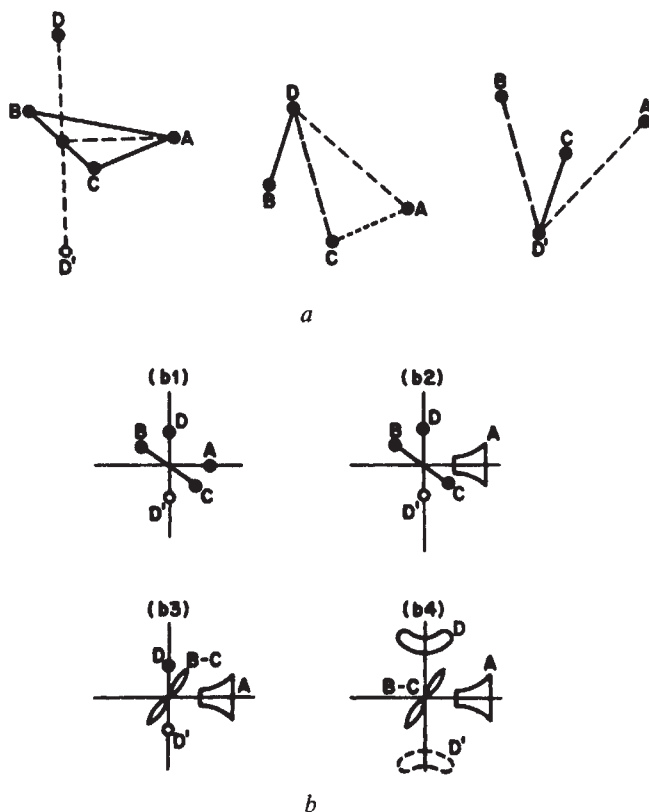


Fig. 3 The four-disk method and its generalization to generate isometric dual micropatterns that when randomly thrown, respectively, yield texture pairs with identical second-order statistics. *a* Depicts the four-disk method of B.J. *et al.*¹⁰. One micropattern is composed of the four identical disks A, B, C and D, such that A is centred on the *x*-axis, B and C are centric symmetric to the origin, while D is centered on the *y*-axis. The dual micropattern contains D' in place of D, that is symmetric with respect to the origin of D. The dual micropatterns are isometric, but there exist triangles (ABD) that cannot fall on the dual micropattern (after B.J. *et al.*¹⁰). *b*, Generalization of the four-disk method of four steps B1, B2, B3 and B4, where disk A can be any object with bilateral symmetry across the *x*-axis. BC disks can be replaced by any centric symmetric object, and D and D' can be any objects with bilateral symmetry across the *y*-axis, and centric symmetric to each other (after Caelli *et al.*¹³).

discrimination exists if one considers feature detectors with receptive fields (of ϵ or smaller extent) as are found in the visual system of vertebrates¹⁻⁴. Texture segregation could be explained by the frequent stimulation of these detectors in the left field, whereas no such detectors are activated in the right field.

These examples indicate that effortlessly discriminable textures with different second- or first-order statistics—which include most, if not all, natural textures—also seem to differ locally. So whether the pre-attentive visual system merely detects the occurrence of certain local features that are present in one texture and absent in another, or analyses some global statistical parameter that distinguishes these textures is still undecided. At this point, some readers might favour the theory of feature detectors, influenced in their choice by the dramatic neurophysiological discoveries of such detectors in the visual systems of frog, cat and monkey by such workers as Kuffler¹, Barlow², Lettvin *et al.*³ and Hubel and Wiesel⁴. However, Barlow, who pioneered the notion of a receptive field in neurophysiology², was unable to find psychophysical evidence for elongated receptive fields in human texture perception. He recently studied the detection of one rectangular random-dot array surrounded by another having different first-order statistics⁵ and found, to his surprise, that performance of detection did not change with the aspect ratio of the target rectangle, despite the fact that most receptive fields in the monkey cortex are highly elongated⁶. Indeed, it took 16 years to find evidence that local feature detectors participate in texture perception.

The iso-second-order texture paradigm

Figure 1*a*, *b* and *c* demonstrate that the pre-attentive visual system might process differences in second-order statistics, or just detect conspicuous local differences, or perhaps performs both operations. In 1962, to test the limit of statistical computational capabilities of the pre-attentive visual system, I posed the question: would it be possible to create texture pairs with identical second-order statistics, but different third- and higher-order statistics; and could such iso-second-order textures still be discriminated⁷? The mathematicians Rosenblatt and Slepian solved the first part of this question for Markov processes⁸, and in probing the second part of the question, I observed that iso-second-order Markov textures of densely packed stochastic dot arrays were usually indistinguishable without scrutiny⁷. Recently, a new class of two-dimensional, non-Markov stochastic dot textures has been created by Pratt *et al.*⁹, and these were also indistinguishable when their second-order statistics

agreed. From these observations one could conjecture that "the pre-attentive textural system cannot globally compute third- or higher-order statistics". This will be called the 'modified Julesz conjecture'. (The original Julesz conjecture, which hypothesized that "iso-second-order textures are indistinguishable", has been disproved and will be discussed below.)

The main problem with these indistinguishable iso-second-order stochastic dot textures is that they are also locally indistinguishable. It would be more convincing to test the modified Julesz conjecture using iso-second-order texture pairs whose elements are conspicuously different yet as textures are indistinguishable. Recently I and my co-workers¹⁰⁻¹⁴ have succeeded in generating several classes of iso-second-order texture pairs that are globally (that is, as textures) indistinguishable but locally (that is, their elements) can be discriminated. Figure 2a, b and c demonstrate three such texture pairs.

The texture pair in Fig. 2a is composed of identical non-overlapping elements ('R') and their mirror-images in all possible random orientations. Such texture pairs, as I and my co-workers¹⁰ have shown, have identical second- but different third- and higher-order statistics. (Indeed, when one of these textures is printed on a glass sheet, the other side shows the mirror-image texture, and obviously the dot and dipole statistics must agree, but the triangle statistics differ.) The texture pair in Fig. 2a is sufficiently indistinguishable that it is unlikely, without prior prompting, that one would suspect that this texture pair is not a single coherent texture. One has to scrutinize the textures element by element and perform a 'mental rotation' in the Shepard and Metzler sense¹⁵. Indeed, even when the pair of elements is presented in isolation, the two elements cannot be discriminated in a 160-ms brief flash followed by erasure if they are oriented far from parallel.

Figure 2b depicts an even more interesting case. This iso-second-order texture pair and many others were generated by the generalization of the four-disk method described by myself and my co-workers¹² as developed by Caelli *et al.*¹³. Figure 3 legend describes how the four-disk method and its generalization work. One can prove the geometry that the micropattern composed of the four disks ABCD, and its partner composed of the disks ABCD' are isometric: to any two points (dipole)

selected in one micropattern there exists a corresponding dipole in the dual micropattern. Although these dual dipoles usually have different orientations, the textures formed by the random throwing of the micropatterns in all orientations result in identical dipole statistics. The generalization of the four-disk method is as follows. One can easily verify that disk A can be chosen to be any shape with bilateral symmetry to the *x*-axis. B and C disks can become any shape with centric symmetry through the origin, while D and D' can be replaced by any shape with bilateral symmetry across the *y*-axis and equally distant from the origin. The dual micropatterns composed of these three forms again are isometric. However, there are triangles whose three vertices will fall on one micropattern, but not on its dual micropattern. Thus, the texture pair in Fig. 2b has the same second-order, but different third-order statistics. Here the elements of the two indistinguishable textures are pre-attentively indistinguishable although in this case with focal attention they can be easily told apart. After all, one would expect that simple cortical units whose elongated receptive fields match the rectangles in these texture elements should differentially fire for zero, one or two X's being contained in these rectangles. That no textural discrimination is obtained suggests two possibilities: (1) differences in third- or higher-order statistics are not processed; and (2) the output of local feature analysers is linearly averaged. The latter statement refers to the observation that areas covered by rectangles containing only single X's when linearly averaged have the same contribution as rectangles containing zero or two X's when these occur with 0.5 probability and one assumes that the simple cortical units are themselves linear.

Figure 2c is perhaps the most instructive example. It is also generated by the technique described in Fig. 3b. Here the indistinguishable iso-second-order texture pair is composed of dual elements, respectively, that in isolation are pre-attentively discriminable. Thus, when the dual elements are briefly flashed (followed by erasure) and the two elements placed 6 deg arc apart (3 deg arc from the fixation point) they can be discriminated, regardless of their orientations. The lack of texture discrimination in Fig. 2c is rather unexpected. If one were to assume that Kuffler units and elongated blob detectors of the Hubel and Wiesel type are involved in perception—as attested

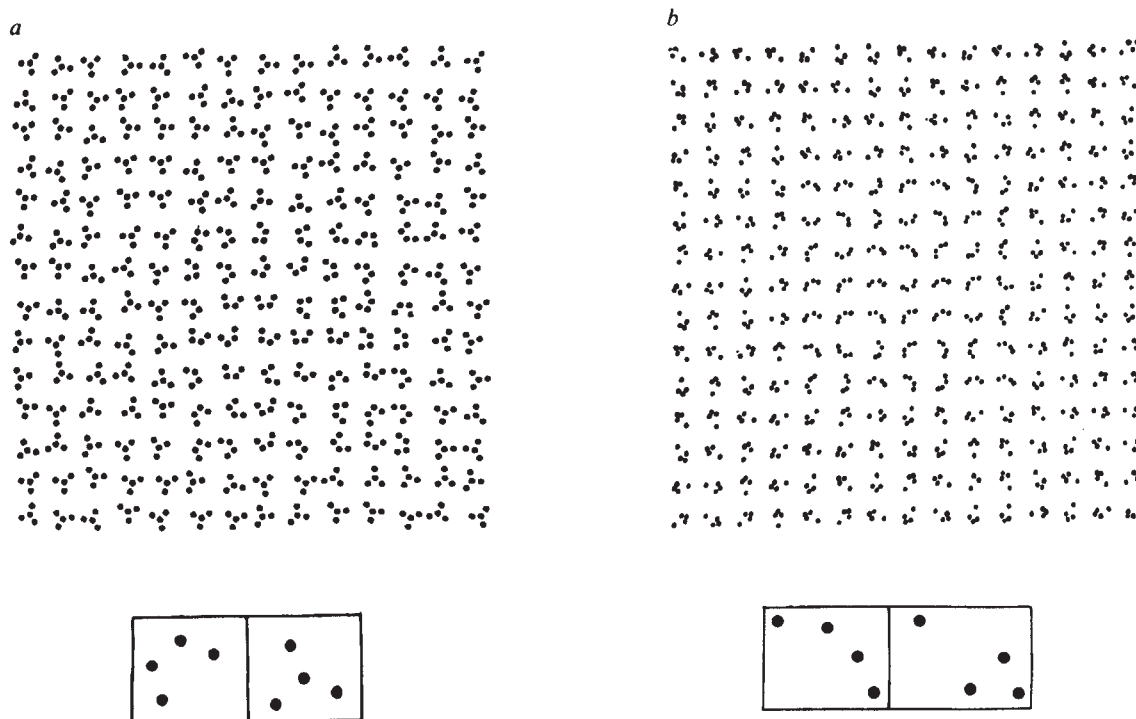


Fig. 4 Iso-second-order texture pair generated by the four-disk method: a, just below threshold of pre-attentive texture discrimination (from B.J. *et al.*¹⁰); b, well above threshold. Pre-attentive texture discrimination is based on local conspicuous features of quasi-collinearity of disks. (From Caelli and Julesz¹².)

to by the fact that the 'open' and 'compact' dual elements can be discriminated—it is rather surprising that pools of such detectors (differentially tuned to the larger open and smaller compact elements) are not utilized in pre-attentive texture discrimination. This problem will be resolved in the following sections.

It had been shown that iso-second-order textures exist that are indistinguishable globally even when locally their elements are either attentively, or even pre-attentively, distinguishable. Because the second-order statistics determine the autocorrelation function, and the Fourier transform of the autocorrelation function is the power spectrum, these iso-second-order textures have identical autocorrelation functions and identical power spectra. Thus, the pre-attentive visual system ignores the phase (position) spectrum that is so conspicuous when the elements are viewed by focal attention. This implies the operation of two visual systems, as has been suggested by many workers in the fields of attention and cognition. The attentive system uses focal attention scanned serially. The pre-attentive system uses distributed attention that is mediated by a parallel process. The insensitivity of pre-attentive texture perception to the position of texture elements directly implies a parallel system.

The role of local elements in iso-second-order texture discrimination

The existence of many indistinguishable iso-second-order textures has established that the pre-attentive visual system is unable to process statistical information beyond the second order. The next question is whether iso-second-order texture pairs do exist that yield pre-attentive texture discrimination. If they do, such texture discrimination must be the result of local features. As we have seen that many seemingly conspicuous features do not yield texture discrimination in the iso-second-order statistical constraint, those local features that might yield texture discrimination should be very special ones. They should be regarded as the basic elements of pre-attentive perception, and I have named such hypothetical elements 'textons'¹⁶.

Indeed, in 1978 several new iso-second-order texture classes were discovered that yield strong discrimination based on very conspicuous local features. The first was discovered by Caelli

and myself¹² using the four-disk method given in Fig. 3a. In Fig. 4a a case is shown (using the dual micropatterns shown in Fig. 3a) that is just below the threshold of pre-attentive texture discrimination, although the open and closed texture elements in isolation are pre-attentively discriminable. However, it was possible to open up the open elements further so that the four disk micropatterns became quasi collinear (while keeping the dual elements still 'closed'). As shown in Fig. 4b, presenting the quasi-collinear features in only one texture region resulted in strong pre-attentive texture discrimination. This local feature might be visually extracted by local detectors tuned to elongated blobs (of given width, orientations and aspect ratios).

Several other iso-second-order textures have since been found that yield pre-attentive texture discrimination^{12-14,16-18}. In each case, pre-attentively discriminable local conspicuous features such as 'closure', 'corner', 'connectivity' and 'granularity' were prominent. Figure 5a, b and c show a few typical iso-second-order texture pairs that yield pre-attentive texture discrimination.

Figure 5a and b were obtained by the generalized four-disk method of Fig. 3b, and discrimination seems to be due to the conspicuous local features of closure and connectivity, respectively. Figure 5c is an iso-third-order (hence also iso-second-order) texture pair created by a new stochastic process of Julesz, Gilbert and Victor¹⁴ which shows that, contrary to what might be believed, perceived granularity need not be determined by the power spectrum, nor even by the second- and third-order statistics but can be a fourth-order property! Here again, as in the case of quasi-collinear disks, it seems that elongated blobs of different widths, length and orientation, and perhaps of different first-order statistics in small, local neighbourhoods are the local conspicuous features yielding texture discrimination.

The role of terminators in texture discrimination

Only the quasi-collinear structures (line segments) and elongated blobs in general have so far been identified as textons. Are other conspicuous local features such as closure, corner and connectivity (Fig. 5a, b) also textons? Fortunately, I have recently found that this is not so¹⁶. In one experiment, dual

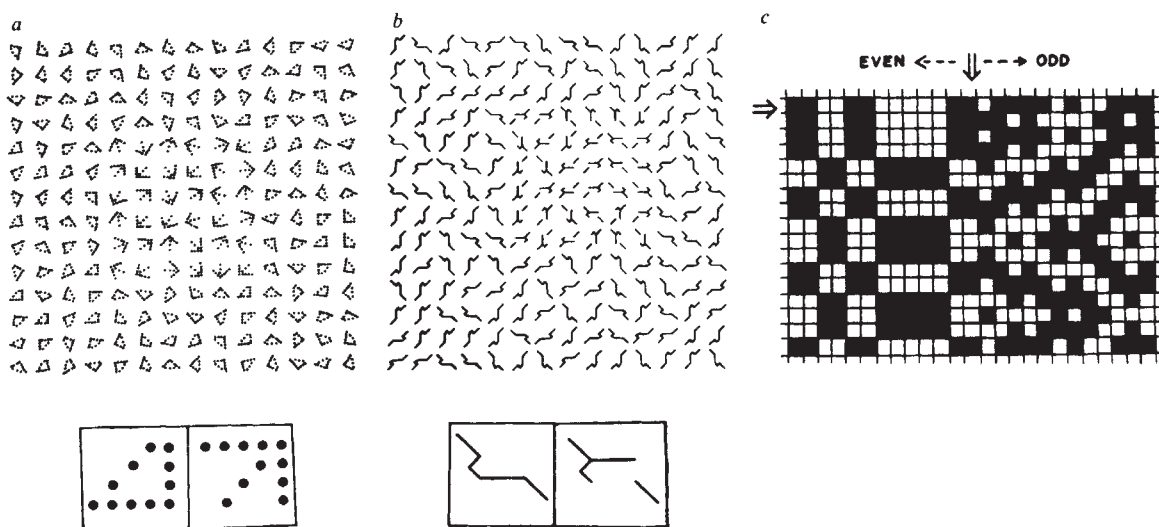


Fig. 5 Discriminable iso-second-order texture pairs based on local conspicuous features of: a, 'closure' (from Caelli *et al.*¹³); b, 'connectivity' (from B.J.¹⁶; a and b were generated by the method described in Fig. 3b); c, 'granularity'. This texture pair has identical third-order (hence identical second-order) statistics (from B.J. *et al.*¹⁷). The small squares in the first row and middle column are selected black and white at random while each 2×2 square left of the middle column contains even numbers of black squares and right of the middle column contains odd numbers of black squares. However, two basic local features (textons) suffice to explain these differences. In c textons are elongated blobs of different sizes, while for a and b it is the difference in the number of end-of-lines (terminators) of the dual elements that yields texture discrimination.

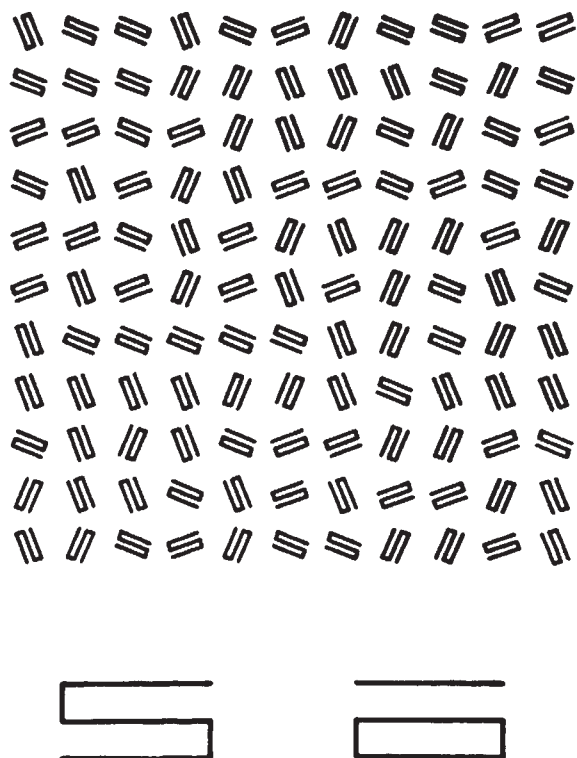


Fig. 6 Demonstration that if the number of terminators (end-of-lines) agrees, then in pre-attentive texture discrimination their exact positions are ignored. This texture pair is indistinguishable in spite of the fact that the open/closed and connected/unconnected features are juxtaposed in the dual elements; however, line segments and the number of terminators agree.

texture elements were selected in which open/closed and connected/unconnected features were simultaneously juxtaposed (insert in Fig. 6). When these formed texture pairs they could not be pre-attentively discriminated from the surround (Fig. 6). One might suspect that the texture pair in Fig. 6 is indistinguishable (similar to the indistinguishable pair in Fig. 2c) because, in addition to having the same line segments, the number of the end points (terminators) of these line segments is also the same in the dual texture elements. Furthermore, the fact that the texture pair in Fig. 6, composed of 'S' and '10'-shaped elements, is indistinguishable, also shows that the exact position of the terminators is not perceived pre-attentively.

Indeed, if one inspects the discriminable iso-second-order texture pairs in Fig. 5a and b, the basis of discrimination can be seen to be the difference in terminator number. The pre-attentive visual system, evidently, cannot determine the location of terminators, but can count their numbers (or density) or their first-order statistics. Thus, the putative textons of corner, closure and connectivity can actually be simply described by differences in terminator numbers.

Therefore, besides colour, there are two additional texton classes: elongated blobs (of given orientation, width and aspect ratio) and their terminators. Pre-attentive texture discrimination is based either on the difference in the textons or the difference in the first-order statistics (or some parameter defined by the first-order statistic, such as density or standard deviation) of the textons.

Thus, the original Julesz conjecture has been refuted: there are iso-second-order textures that can be discriminated. However, the modified Julesz conjecture seems to hold: the pre-attentive textural system cannot compute statistical parameters higher than second order. Therefore, discrimination

in iso-second-order textures involves differences in local conspicuous features, called textons.

Interaction between textons

One can even strengthen the modified Julesz conjecture by raising the possibility that the pre-attentive textural system globally cannot even compute second-order statistical parameters, but can evaluate only the first-order statistics of textons. If this were the case, then for the pre-attentive system the interactions between textons would be simple, based on some first-order statistical parameters.

An experiment, depicted by Fig. 7 (and published here for the first time) suggests such a possibility. In Fig. 7a the same micropattern comprised of a 4×4 dot array of randomly selected 8 white and 8 black dots is repeated many times horizontally and vertically with an 8-dot period (leaving 4-dot-wide blank gaps between the micropatterns). This periodically covered area is flanked on two sides by an area of densely packed random dots of black and white. Figure 7b is derived from Fig. 7a by filling the blank gaps between the periodic micropatterns with densely packed black and white random dots. The texture pair in Fig. 7b (composed of the area with periodic micropatterns and the neighbouring random area) have identical first-order statistics but very different second-order statistics (and very different autocorrelations). Nevertheless, the texture pair appears indistinguishable. On the other hand, if the 4×4 dot micropattern contains a texton (consisting of 8 white and 8 black dots forming stripes) as shown in Fig. 7c and d (with and without blank gaps between the periodic micropatterns, respectively), Fig. 7d yields strong texture discrimination, based on the dense occurrence of textons that are practically absent in the other texture. Indeed, the largest difference in the autocorrelations between the periodic and aperiodic textures occurs at the 8-dot periods, and this difference is the same for the indistinguishable texture pair in Fig. 7b and the strongly distinguishable one in Fig. 7d. These examples clearly indicate that texture discrimination is not the result of differences in second-order statistics, but is based on density changes in textons. Caelli and myself¹⁹, who studied discrimination of texture pairs composed of dot pairs (dipoles) having different orientational ranges, could predict perceptual performance based on the first-order statistic of dipole orientation alone.

It is interesting that if texture elements and their dual partners differ in their textons, even a single element can be pre-attentively perceived as being different amidst many iso-second-order dual partners (Fig. 8a).

Recently, Burt and I became interested in the interactions between textons, or interactions between the first-order statistics of different textons²⁰. We were particularly interested in cooperative interactions, and to this end we tachistoscopically presented two or more target micropatterns embedded in iso-second-order dual partners, either dispersed or grouped, as shown in Fig. 8a and b. We found that if the critical (unshared) texton belonged to the target micropattern and not the surround, there was no cooperativity. The dispersed and grouped conditions were equally detected, and probability of detection increased with the number of target micropatterns (that is, with the number of the critical textons). Also, probability of detection was greater when the critical texton belonged to the target micropattern instead of the surround. In another texture paradigm, Beck²¹ noted that the presence of features (textons) in the target is more perceptible than their absence.

If the critical texton(s) are absent from the target micropatterns (and thus belong to the surround), then the grouped condition is better perceived than the dispersed. However, this 'cooperativity' is of a rather simple kind. If we assume pools (layers) of similar textons corresponding to various retinal positions, then the presence of a critical texton in a target micropattern will cause activity in the critical pool (and increased activity with many targets, according to their number) regardless of whether these textons are dispersed or grouped. However, the absence of critical textons in the target micropatterns means

that these textons belong to the micropatterns in the surround, and densely stimulate the corresponding texton layer. To be certain that a texton-free area is not a chance fluctuation, this area must be significantly larger than the mean distance between the micropatterns of the surround. Obviously, grouped target micropatterns assure a much larger texton-free area than do dispersed ones.

Finally, we also observed that with long practice, involving several hundred trials, some indistinguishable iso-second-order texture pairs (such as Fig. 2c) could become pre-attentively discriminable. This might seem contradictory to the recent cognitive studies of Treisman²², who conjectured that conjunctions of features (she used colours and shapes) cannot be pre-attentively perceived, even with practice, but require serial, element-by-element search. The research reported here agrees with her findings. Only disjunctive texton groups (that is, differences in textons) can be perceived pre-attentively (that is, as a parallel process, regardless of element number). The reason the conjunctions of textons that form the dual elements in Fig. 2c can be learned might be that these open and closed elements can have different stimulatory effects on elongated blob detectors,

which are themselves textons. Their detection escaped attention before the task was mastered.

Textons and Marr's 'primal sketch'

It was only after 18 years that I and my co-workers discovered how the simple, complex and hypercomplex cortical feature detectors of the neurophysiologists would correspond to the texton detectors of elongated blobs and their terminators. Thus, it took that long to overcome the initial scepticism, and show that the feature detectors of the neurophysiologist could be utilized in pre-attentive perception. Marr²³, within the framework of artificial intelligence (machine vision), proposed his 'primal sketch' model based on local intensity changes across edges, elongated blobs (lines) and end-of-lines, and their first-order statistics. In essence, the input is spatially filtered and convoluted with masks of given shapes, widths and orientations, similar to the 'Mexican hat function' shape receptive fields of simple cells of Hubel and Wiesel⁶. Marr also introduced inhibition between such simple units (particularly of perpendicular

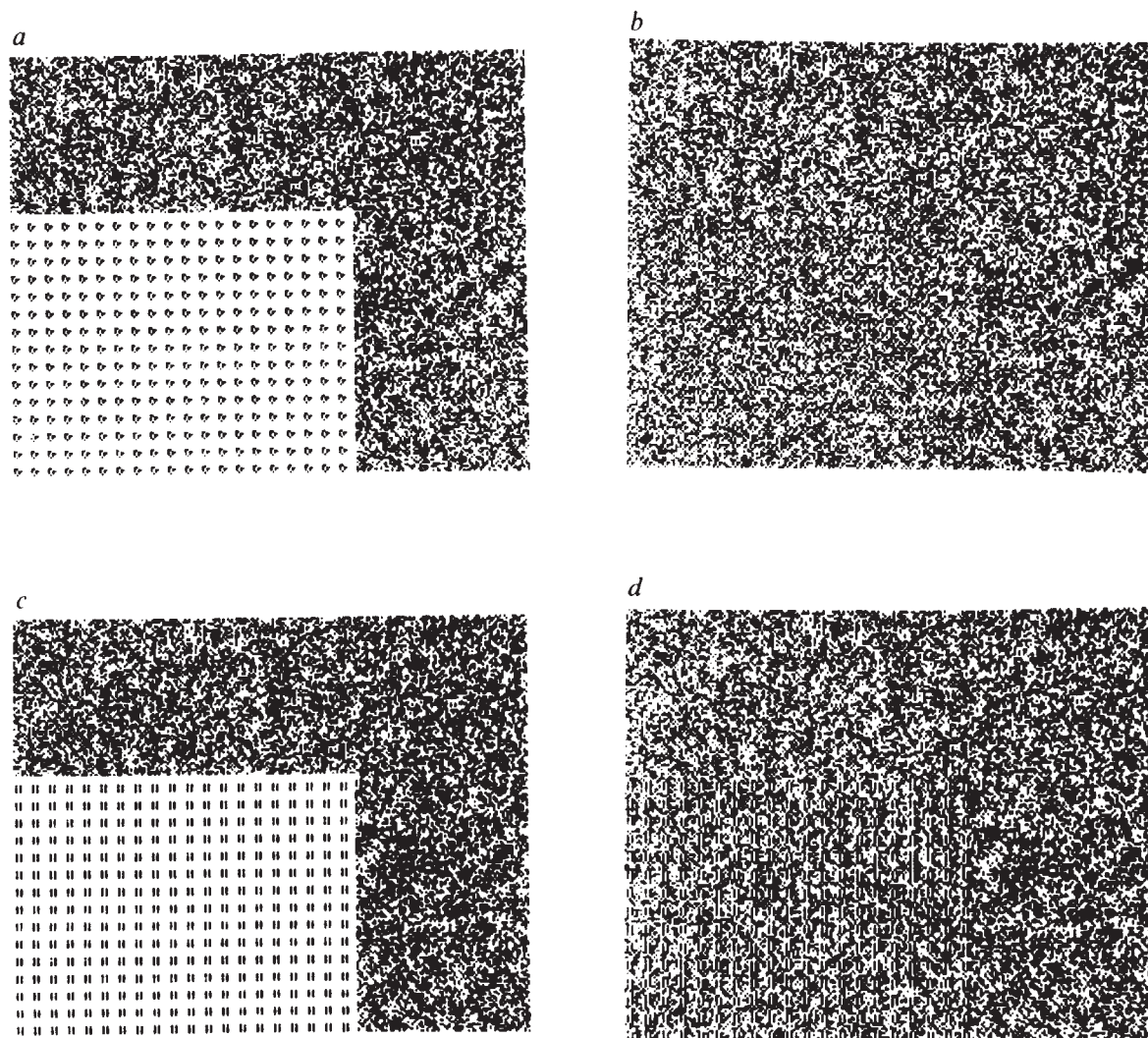


Fig. 7 Demonstration that the pre-attentive textural system cannot process globally differences in second-order statistics, and only first-order statistics of textons yield texture discrimination. *a*, Periodically repeated 4×4 dot micropattern that does not contain textons, flanked by randomly dotted areas. *b*, Same as *a*, except that the blank gaps between the periodic micropatterns are filled with random dots. The second-order statistics are very different between the area composed of periodic micropatterns and its random neighbour, and yet they appear indistinguishable. *c*, Same as *a*, except that the 4×4 dot micropattern contains textons of periodic stripes. *d*, Same as *c*, except that the noise insertion described in *b* is carried out. Now strong texture discrimination is experienced based on the dense occurrence of textons that are missing in the neighbouring area.

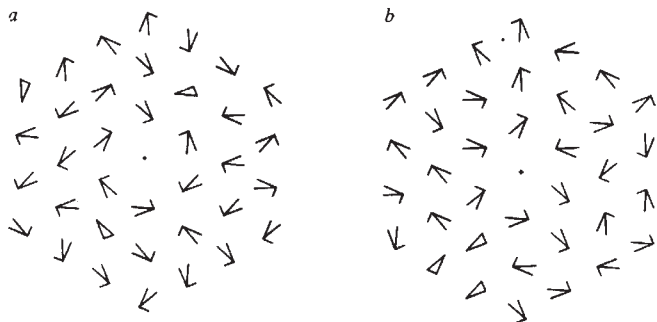


Fig. 8 Demonstration that texton differences can be pre-attentively detected even if the target micropatterns are dispersed within many dual elements as in *a*; in *b* a few target elements are grouped. With centre fixation and briefly flashed (using erasure), the dispersed and grouped case yields identical detection when the unshared textons belong to the target.

units) giving rise to terminators, trying to emulate all the known feature detectors of the neurophysiologists, and devised algorithms that would emulate pre-attentive vision. Thus, Marr was the first to stress the role of terminators in texture perception. However, he went a step further and introduced 'place tokens', higher-order collections of blobs (lines) based on several grouping operations that do not depend on semantic content. Space does not permit a review of this important model, but let me quote Marr (ref. 23, p. 510): 'Julesz (1975, p. 43) mentioned in an aside the possibility that texture vision may rest on 'first-order statistics of various simple feature extractors' but this idea requires the concept of the primal sketch and of recursively applied grouping before it can be brought into fruition.' Although Marr's primal sketch model goes beyond texture perception, into pre-attentive vision and beyond, neither he nor neurophysiologists or researchers in artificial intelligence could have guessed that in texture discrimination only the number of terminators has perceptual significance and that their position is ignored. Similarly, without careful psychological research, one cannot guess how real and virtual dipoles (between two place tokens) affect perception. For example, the primal sketch model regards them as equal, which led to incorrect predictions in texture discrimination as shown by Schatz²⁴. Also, the finding that in texture perception only three or more quasi-collinear place tokens act as a real line shows the importance of perceptual experiments¹⁶. It remains to be seen whether, besides the three texton classes, some other textons will be found in pre-attentive texture discrimination—the more complex place-tokens of Marr. On the other hand, anyone who wants to go beyond texture perception should carefully study Marr's discerning ideas.

Obviously, artificial intelligence, neurophysiology and psychology can aid each other, and the fact that the search for textons led to findings that agree with ideas and discoveries in artificial intelligence and neurophysiology is most gratifying.

Conclusion

It was shown that contrary to the Gestaltists' belief, a highly global percept, texture, can be decomposed into elementary

units, the texton classes of colours, elongated blobs of specific widths, orientations and aspect ratios, and the terminators of these elongated blobs.

One might ask whether sinusoidal gratings, so popular in vision research, could be used in texture perception. After all, the detection of compound sinusoidal gratings does not depend on phase (if the ratio of the gratings is 3:1 or higher), as shown by Graham and Nachmias²⁵. This phase independence at threshold of detection, however, should not be confused with the phase independence of suprathreshold discrimination often found in iso-second-order textures. While textures with identical second-order statistics have identical power spectra, the converse is not true. One cannot profitably study textures having only identical power spectra, because changes in phase between sinusoidal grating components dramatically change the first-order statistics, and thus give rise to texture discrimination for trivial reasons. Furthermore, global Fourier analysis cannot reveal the occurrence of local textons, particularly terminators²⁶ (also implied by the demonstrations of Fig. 7 and ref. 28).

Thus, through the iso-second-order texture paradigm we can restrict the global computational powers of pre-attentive perception and identify local conspicuous features, the textons. Whatever the final number of these texton classes will be, it is evident that for texture discrimination the Gestaltists' view has not been corroborated: the global percept of texture was found to be decomposable into more basic elements. Only if pre-attentively discriminable texture pairs were to be discovered, with its elements (or local aggregates of these elements) found to be pre-attentively indistinguishable, would my modified conjecture be refuted.

This article was restricted mainly to research based on the iso-second-order texture paradigm. The reader interested in more conventional texture research, particularly in the more complex problems of textural grouping and recognition, and in practical problems such as that of automating the search for malignancy in clinical tissues, might find additional references in ref. 27.

In conclusion, let me draw an analogy to the phase-transitions of physics, in which symmetry (invariance) laws and the breaking of these symmetries prevail. Textons in pre-attentive perception obey such a symmetry law. They seem, within limits, to be invariant under positional and scaling transformations. These symmetries of textons cannot be broken by pre-attentive and peripheral vision, as the 'coupling' that locks textons in their proper positions is missing (as if the 'attentional temperature' in these systems were too high). Only by inspecting areas where the densities of textons differ, thus switching to focal attention, can our visual system break the texton symmetries. Only within a small disk of focal attention are the textons coupled (as if this disk were 'cooled' below a critical temperature), permitting the formation of higher percepts (thus enabling us to distinguish, say, an R from its mirror image). This analogy mainly serves to pinpoint the major implication of our findings, that most of the single cortical feature analysers (outside foveal representation) might not be connected directly to each other (but interact only in aggregate). This relative phase insensitivity might also account for the apparent poor spatial resolution of our peripheral vision, which, however, is quite acute for textons, particularly end-of lines.

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