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A Theory of Preattentive Texture Discrimination Based on First-Order Statistics of Textons

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Abstract. The many indistinguishable texture pairs having identical second-, but different third- and higher-order statistics, led to the conjecture that *globally* the preattentive texture discrimination system cannot process statistical parameters of third- or higher-order. Thus in cases when iso-second-order textures yield discrimination this must be based on *local* conspicuous features called *textons* (Julesz, 1980). Here it is shown that globally even second-order statistical parameters, such as autocorrelation, cannot be processed by the textural system, and texture discrimination is solely the result of first-order statistics (density) of textons. It is also shown that the perceivable distance of statistical constraints (coherence distance) in densely packed stochastic textures is very short, four dots or less. As of now, only three texton classes were found: color, elongated blobs (line segments) of given width, orientation, and length, and the terminators (end-points) of these elongated blobs. The strength of these textons is demonstrated by several examples.

1. Introduction

In recent years several new methods were discovered to implement the iso-second-order texture paradigm of Julesz (1962), that is to generate stochastic texture pairs with identical second-order statistics and study their effortless (preattentive) discrimination. The two main findings are as follows:

A.

A great variety of iso-second-order texture pairs have been found that yielded no discrimination, in spite of the fact that their third- and higher-order statistics differed. [Such a typical indistinguishable iso-second-order texture pair is shown in Fig. 1A, generated by the generalized four-disk method of Caelli et al. (1978).] These results suggest that the preattentive texture discrimination system cannot globally process third- and higher-order statistics. So, if iso-second-order texture pairs yield effortless discrimination, this must be the result of local features, to be called textons (Julesz, 1980).

B.

Recently, many effortlessly discriminable iso-second-order texture pairs have been discovered based on local conspicuous features of quasi-collinearity, elongated blobs (of specific orientation, width and length), corner, connectivity, closure, etc., by Caelli and Julesz (1978), Caelli et al. (1978), Julesz et al. (1978), and Victor and Brodie (1978). A typical strongly discriminable iso-second-order texture is shown in Fig. 1B. However, as Julesz (1980) suggested, besides color, only two other textons exist: elongated blobs, and their terminators. All the other local conspicuous features of corner, closure, and connectivity can be expressed by the two texton classes. Indeed, if the *number* of textons agrees, connectivity and closure can be juxtaposed in the dual elements which by themselves are preattentively discriminable, yet the texture pair they form appears indistinguishable (see Fig. 1C). The strong discrimination of the texture pair in Fig. 1B is based on a large difference in the number (density) of terminators, while in the indistinguishable texture pair of Fig. 1A both the type and number of elongated blobs (line segments) and the number of their terminators is identical.

In this paper it will be suggested that the preattentive textural system globally cannot even compute second-order statistical parameters, and discrimination is based on first-order statistical parameters of textons. This possibility has been raised previously by Julesz (1975) and Marr (1976), who suggested that

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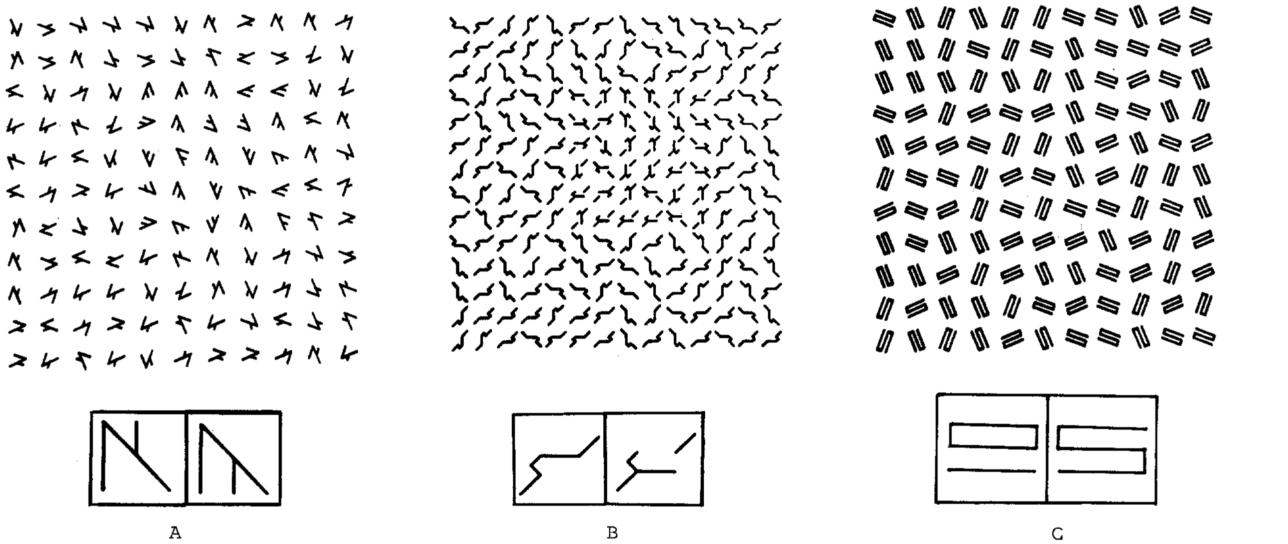

Fig. 1A–C. Demonstration of recent main findings in preattentive texture discrimination: **A** indistinguishable texture pair with identical second-order statistics, suggesting that globally third- and higher-order statistical differences cannot be processed; **B** distinguishable texture pair with identical second-order statistics, based on local conspicuous features (textons), in this case difference in the number of end-of lines (terminators); and **C** if the textons of elongated blobs (line segments) and their terminators have the same numbers (densities) no preattentive texture discrimination can result. (From Julesz, 1980)

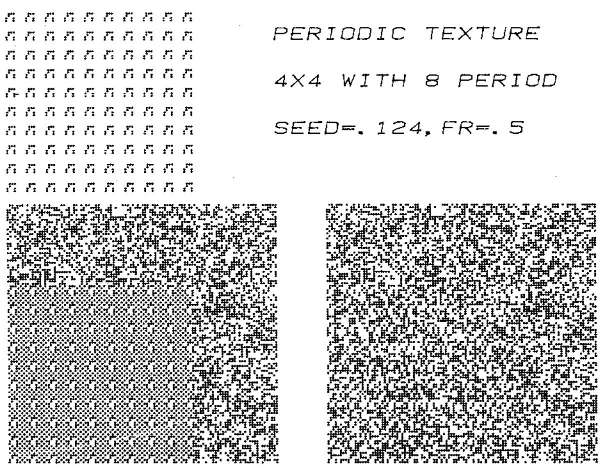

Fig. 2. Demonstration that large differences in second-order statistical parameters (e.g., in autocorrelations) cannot be perceived if the periodically repeated micropattern (of 4 × 4 dots containing 8 black and 8 white dots) is relatively texton free. The right array is similar to the left bottom array, except the checkerboard texture between the repeated micropatterns is filled by random black and white dots. This area with 8 dot periodicity appears as random as its random neighborhood

perhaps only the first-order statistics of conspicuous local features is utilized in preattentive texture perception. However, before the identification of textons such a conjecture was too vague for testing.

It will also be shown that the "coherence distance" in densely packed stochastic dot textures is minimal, three or four dots at most, which indicates that no "long-range-order" can be detected by the textural system.

2. Inability to Detect Autocorrelation Differences in Textures

The experiments reported here are based on the following steps, depicted by Fig. 2. First, a micropattern (here 4 × 4 dots square of 8 black and 8 white randomly selected dots) is periodically repeated (both horizontally and vertically) as shown in the upper left quadrant of Fig. 2 [here the period (P) is 8 dots]. In the lower left quadrant of Fig. 2 the gaps between the similar periodic micropatterns are filled in by a "gray" screen (of a fine checkerboard), and this periodic area is flanked on both sides by a random-dotted area composed of black and white dots of equal probability. Finally the lower right quadrant depicts the texture pair to be studied. It is the same as the pair to its left, except that the 4-dot wide gaps between the periodic micropatterns are now filled by black and white random dots.

The first-order statistics of the periodic area and its random neighborhood agree, but their second-order statistics, and their autocorrelations greatly differ. While for the random neighborhood the autocorrelation is 0.5 for all shifts (expect 1.0 for the zero shift), the periodic area has a $1/4 \times 1 + 3/4 \times 1/2 = 5/8 = 0.625$ autocorrelation at $8N$ dot horizontal and vertical shifts for $N = 1, 2, 3, \ldots$. In spite of this difference, the texture pair cannot be discriminated. As a matter of fact, it requires dot-by-dot scrutiny to detect the periodically repeated micropattern embedded in randomness.

One could argue that a 25% fluctuation in a second-order statistical parameter (the autocorrelation) might be too small for detection. However, in

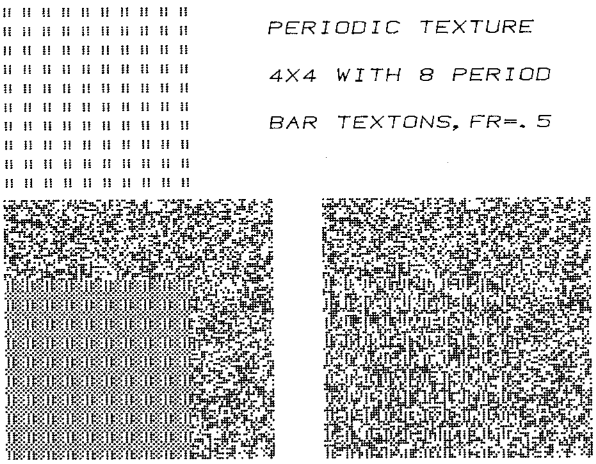

Fig. 3. Similar to Fig. 2 except the periodic micropattern contains textons (vertical bars). Now the periodic area in the right array is clearly different from its random neighborhood. Since the maximum difference in autocorrelation between these two areas is the same as in Fig. 2, texture discrimination is merely due to different first-order statistic (density) of textons

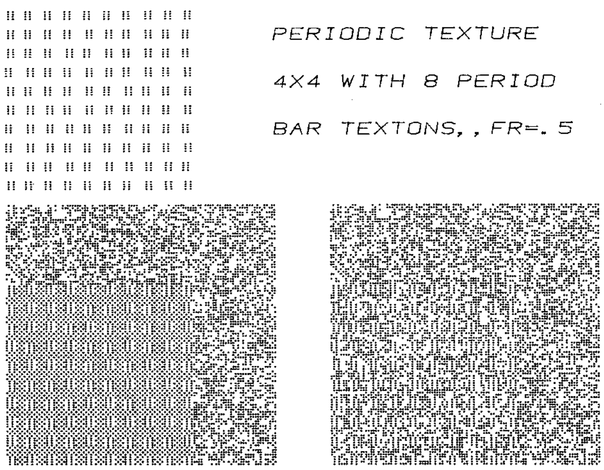

Fig. 4. Similar to Fig. 3 except that the repeated micropatterns containing vertical bars are jittered in phase, thus rendering the maximum difference in autocorrelation the half of the case in Fig. 3. Yet, texture discrimination between the periodic area and its random neighborhood remains strong

Fig. 3 (generated the same way as Fig. 2) the fluctuation in autocorrelation is again 25 %, yet the texture pair yields strong discrimination. Obviously, discrimination is based on the texton-rich periodic micropattern (composed of vertical bars) in one area, that occurs rarely, if at all, in the random neighborhood of Fig. 3.

If the phase (position) of the periodic bars is jittered, thus decreasing the maximum autocorrelation difference by half, as shown in Fig. 4, discrimination is about as strong as for the non-jittered case in Fig. 3.

One can easily search for all possible micropatterns of 4 × 4 dots (or larger sizes) in order to rank-order texture discrimination, and thus establish the texton strength of the micrapattern. Figures 2 and 3 depict

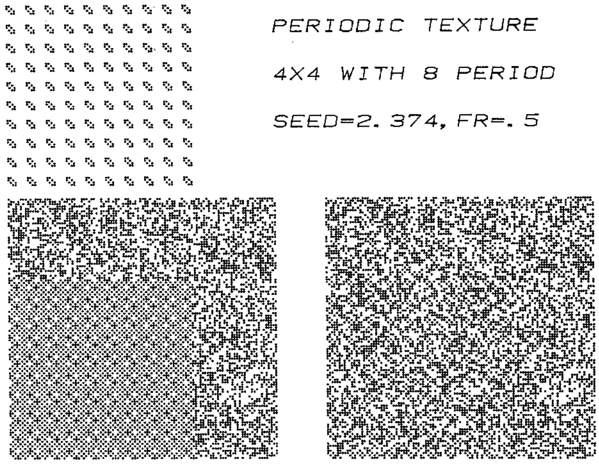

Fig. 5. Another example of indistinguishable texture pairs (in the right array), based on the fact that the periodically repeated micropattern in one area is free of textons

typical cases for the weakest and strongest texton content. In Fig. 5 another indistinguishable texture pair is shown having 8 black and 8 white random dots in the periodic micropattern.

(In the figure captions FR = 0.5 refers to the frequency of black dots in the periodic micropattern, while the "seed" refers to the pseudorandom- number-generator of the HP-85 computer used.)

While it is useful to select the periodic micropattern with FR = 0.5 in order to keep the first-order statistics of the texture pairs identical, small differences in the first-order statistics are not detected if the micropattern does not contain textons different from those in the random neighborhood. For instance, in Fig. 6 the area that contains the periodic pattern does not appear darker than its surround in spite of the fact that FR = 0.5625 in the micropattern in the periodic area. Weak texture discrimination is the result of the elongated outlined blobs (textons). Of course, when FR is much larger than 0.5, discrimination becomes easy, since the micropatterns become large black (or white) blobs.

As long as the micropatterns do not contain textons different from those in the random neighborhood, and/or their densities agree, the texture pairs remain indistinguishable in spite of considerable differences in autocorrelations (that could be easily detected by Fourier analysis). On the other hand, texture pairs with differences in their Fourier spectra similar to the indistinguishable cases will yield discrimination depending on their texton content. [That global Fourier analysis cannot predict the existence of local conspicuous features has been shown by Julesz and Caelli (1979).]

In Fig. 7 the micropattern contains diagonal lines. Texture discrimination is obtained, but is weaker than for the vertical bars in Fig. 3.

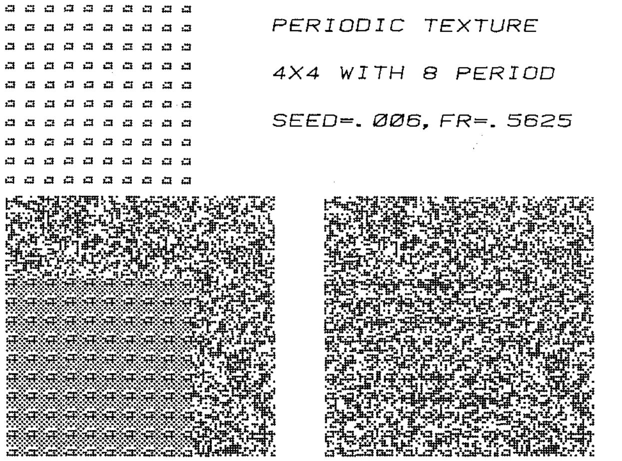

Fig. 6. Similar to Figs. 3 and 5, except that the periodically repeated 4×4 dot micropattern contains 9 black dots (FR=0.5625). However, such small difference in first-order statistic does not make the periodic area appear darker from its random neighborhood. Texture discrimination is based rather on the large number of elongated outlined blobs (textons) in one area

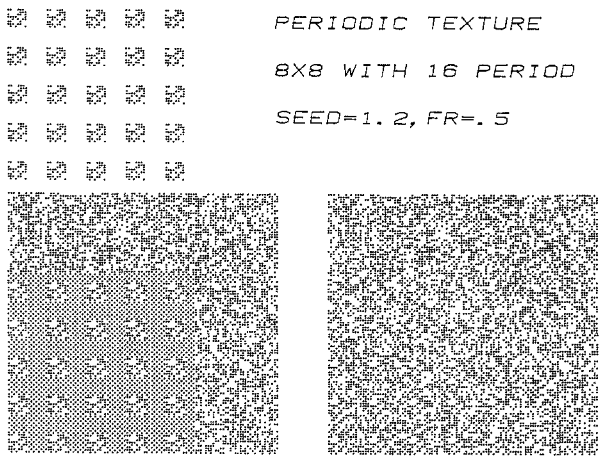

Fig. 8. Similar to Fig. 2, except that the periodically repeated micropattern is now an 8×8 dot square (containing 32 black and 32 white dots) with 16 dot periodicity in the horizontal and vertical directions. The micropattern is relatively texton free, and no texture discrimination is experienced in the right array

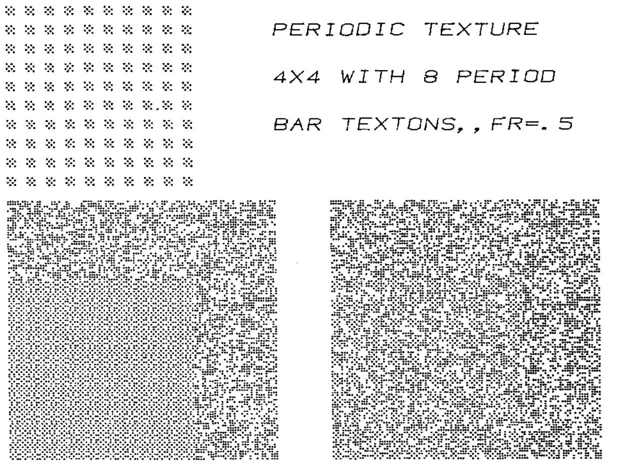

Fig. 7. Similar to Fig. 4, except that the periodically repeated micropattern contains diagonal bars. Texture discrimination is weaker than in Fig. 4 indicating that diagonal bars (line segments) are weaker textons than horizontal and vertical ones

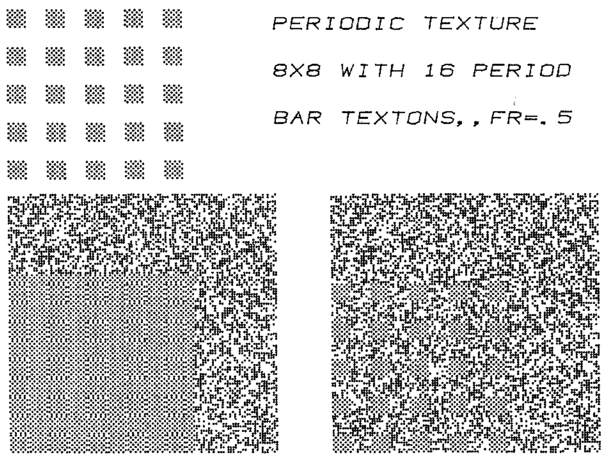

Fig. 9. Same as Fig. 8, except that the periodically repeated micropattern contains diagonal bars. Now texture discrimination is strong. Compared to Fig. 7, it is evident that diagonal bars can be strong textons if they are above critical length

Searching through all 4×4 micropatterns (of FR=0.5) revealed that only those that contained at least 4-dot long horizontal or vertical blobs (of adjacent dots having the same color) could be seen when embedded in noise. A 3 dot long bar might act as a texton if flanked by a 3 dot long bar of opposite color.

With larger micropattern sizes (e.g. 8×8 dots, with a 16 dot period) it requires systematic search to find micropatterns without textons. This seems at first curious, since one would expect that with increased periodicity distance texture discrimination might diminish. However, if the second-order statistics and autocorrelations are not utilized in texture discrimination, but the first-order statistics of textons are, then this finding is explained. With larger micropattern sizes it is not easy to find configurations devoid of some larger black (white) blobs, which then would repeat many times. A typical 8×8 micropattern with FR=0.5 repeated with a 16 dot period is shown in Fig. 8. Discrimination is very weak, if not impossible. If the 8×8 micropattern contains textons, like diagonal bars, discrimination is strong, much stronger than for the 4×4 micropattern size, as shown in Fig. 9. Indeed, a larger local area of dense textons is more detectable than a smaller area in any signal/noise detection paradigm.

Again, whether the periodic bars in the repeated micropatterns occur jittered, as in Fig. 10, or are randomly selected to have vertical or horizontal orientations, as in Fig. 11, does not affect their strong

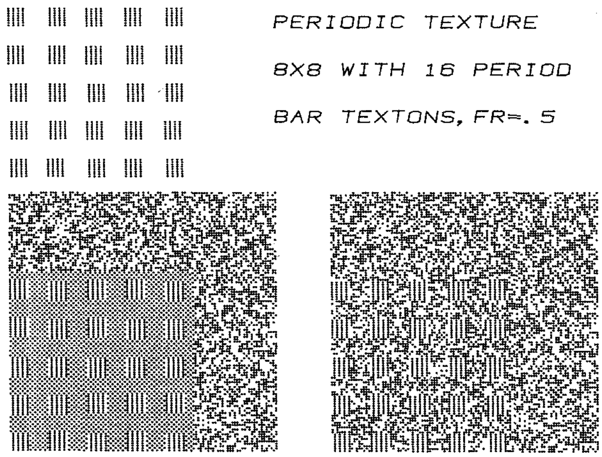

Fig. 10. Same as Fig. 9, except that the periodic micropattern contains vertical bars jittered in phase. Similarly to Fig. 4 strong texture discrimination can be experienced

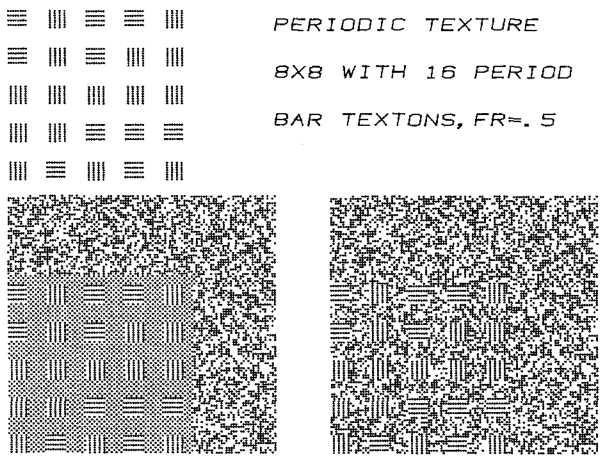

Fig. 11. Same as Fig. 10, except that the periodic micropatterns consist of either vertical or horizontal bars, selected at random. The same strength of texture discrimination can be experienced, even though the maximum autocorrelation difference is half that in Fig. 8 and is identical to that in Fig. 10

discrimination, in spite of the fact that phase jitter reduces differences in autocorrelation by half.

3. Short "Coherence Distance" in Dense Arrays of Dots

Before this demonstration, that second-order statistical parameters cannot be preattentively perceived, it was assumed that the strongly perceivable regularity in periodic patterns was based on autocorrelation. Obviously, a regularly periodic texture composed of textons appears different from a slightly jittered one, as the upper left arrays in Figs. 3 and 4 show. It is probably due to the fact that larger elongated blobs stimulated by the adjacent large blobs have different first-order statistics for the regular and jittered cases.

In the next experiment it will be shown that strongly discriminable iso-second-order and iso-third-order textures based on the method of Julesz et al. (1978) become rapidly indistinguishable as the "coherence distance" exceeds 2 (or 3) dots. What this finding implies is again the following: it is not the global statistics of the third- and higher-order that underlie texture discrimination, since in all examples shown, the statistical differences will be preserved, but, instead, the breaking up of the textons, due to various manipulations.

Figures 12 and 13 show an iso-third-order and an iso-second-order texture pair, respectively, generated by the method of Julesz et al. (1978).

For both Figs. 12A and 13A the first row and first column (and one middle column) contain black and white dots selected at random. In Fig. 12A a "floater" of 2×2 dots square $[P(i,j), P(i+1,j), P(i,j+1), P(i+1, j+1)]$ scans the left (right) half-field row-by-row so that the number of black dots (having a value of 1, while the white dots are 0) in the floater is even (odd). For Fig. 11A the floater is a triangle of three adjacent dots $[P(i,j), P(i+1,j), P(i,j+1)]$, again with an even parity in the left half-field and odd parity in the right one. As shown by Julesz et al. (1978) the texture pair in Fig. 10A has identical third-order statistics. (In the upper region a third area is portrayed with uniformly random black and white dots.) Figure 13A, on the other hand, has identical second-order statistics. Interestingly, all three textured areas in both Figs. 12A and 13A have also the same Fourier power spectrum in spite of their very different granularities.

In Fig. 12B we follow the same procedure as in Fig. 10A, but instead of presenting the dots at each sample point we first skip every other row and column. Thus the sliding square floater is now $[P(i,j), P(i+2,j), P(i,j+2), P(i+2,j+2)]$. In order to define the texture field the first and second rows and columns are now filled with random black and white dots. After the floater has filled every second row and column with dots having even (odd) parity starting from $P(1,1)$, the same procedure is repeated three more times from $P(1,2)$, $P(2,1)$, and $P(2,2)$ starting positions. Figure 14 shows in sequence the way the left half-field of Fig. 12A was generated. The even-odd iso-third-order texture pair can still be discriminated as shown in Fig. 12B. [By the way, statistically constraining every Nth row and column, and repeating the procedure N-times until every raster dot of the texture array is filled with a black or white dot according to even (odd) parity does not affect the iso-third-order statistics of the textures.] This interaction between samples N rows and columns away will be called the *coherence distance of N*.

Figure 12C and D are similar to Fig. 12B; however, in Fig. 12C first the four vertices of the square floater that fall on every *third* row and column $[P(i,j), P(i+3,j), P(i,j+3), P(i+3,j+3)]$ are filled in for even

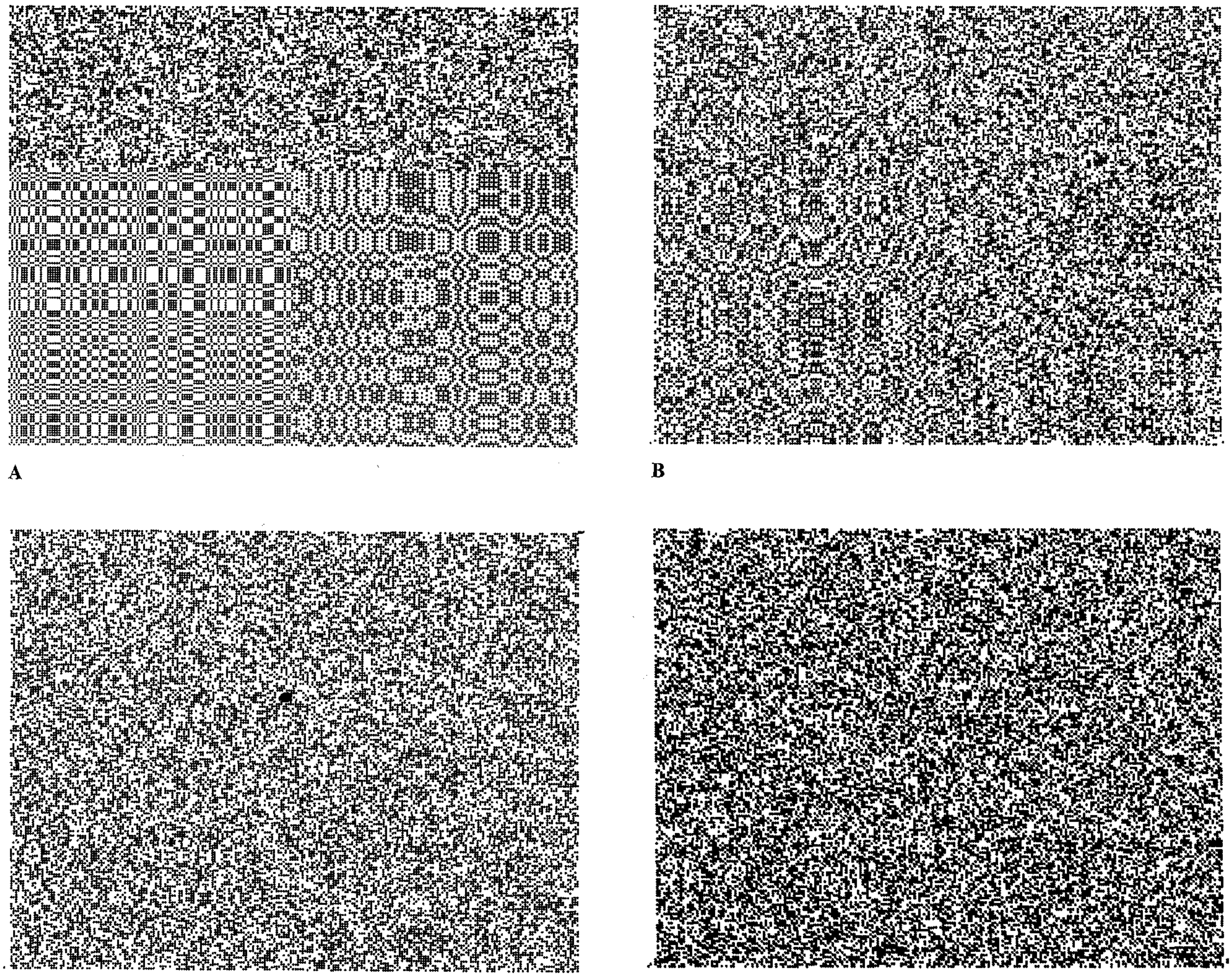

Fig. 12A–D. Textures with identical third-order statistics, generated by a method of Julesz et al. (1978). The bottom row(s) and the leftmost and middle column(s) are selected at random, while a 2×2 square shaped "floater" scans the two half-fields with even/odd parity, respectively. In **A** the square floater contains 4 adjacent cells; in **B** the 4 cells of the floater are 2 dots distant (coherence distance) both horizontally and vertically (as shown in Fig. 14), and this procedure is repeated 4 times until the entire array is densely filled with black and white dots. Texture discrimination is still possible. **C** is similar to **B** except that here the coherence distance is 3 dots; and **D** is similar to **B** except that the coherence distance is increased to 4 dots. In **C** and **D**, textures appear indistinguishable

(odd) parity, and this procedure is repeated 8 more times, until every raster dot is processed. In Fig. 12D the even (odd) constraint extends to every adjacent fourth row and column [$P(i,j)$, $P(i+4,j)$, $P(i,j+4)$), $P(i+4, j+4)$]. Interestingly, Fig. 12C with three dot *coherence distance* in the horizontal and vertical directions already yields indistinguishable texture pairs. It is surprising that stochastic constraints three dot distant are not perceivable! Of course, a four dot coherence distance, as demonstrated in Fig. 12D also yields indistinguishable texture pairs. [Of course, for the cases depicted by Fig. 12C and D, one has to select randomly the first two rows (for Fig. 12D also the first two columns). These randomly selected bottom rows (but not the columns are portrayed in all the figures).]

The same procedure applies for the iso-second-order texture pair depicted by Fig. 13A. Figure 11B–D show textures with stochastic constraints 2, 3 or 4 dots away in the horizontal and vertical directions, respectively. Here, the three dot coherence distance still yields some texture discrimination, but four dot coherence distance yields indistinguishable texture pairs.

Thus, the second main finding of this paper is the relatively short coherence distance (3 or 4 dot length) the perceptual system is restricted to. Here again it seems that only the presence or absence of certain elongated bar textons yields texture discrimination. With increased coherence lengths the extent and orientation of elongated bars diminish, rendering the texture pairs indistinguishable.

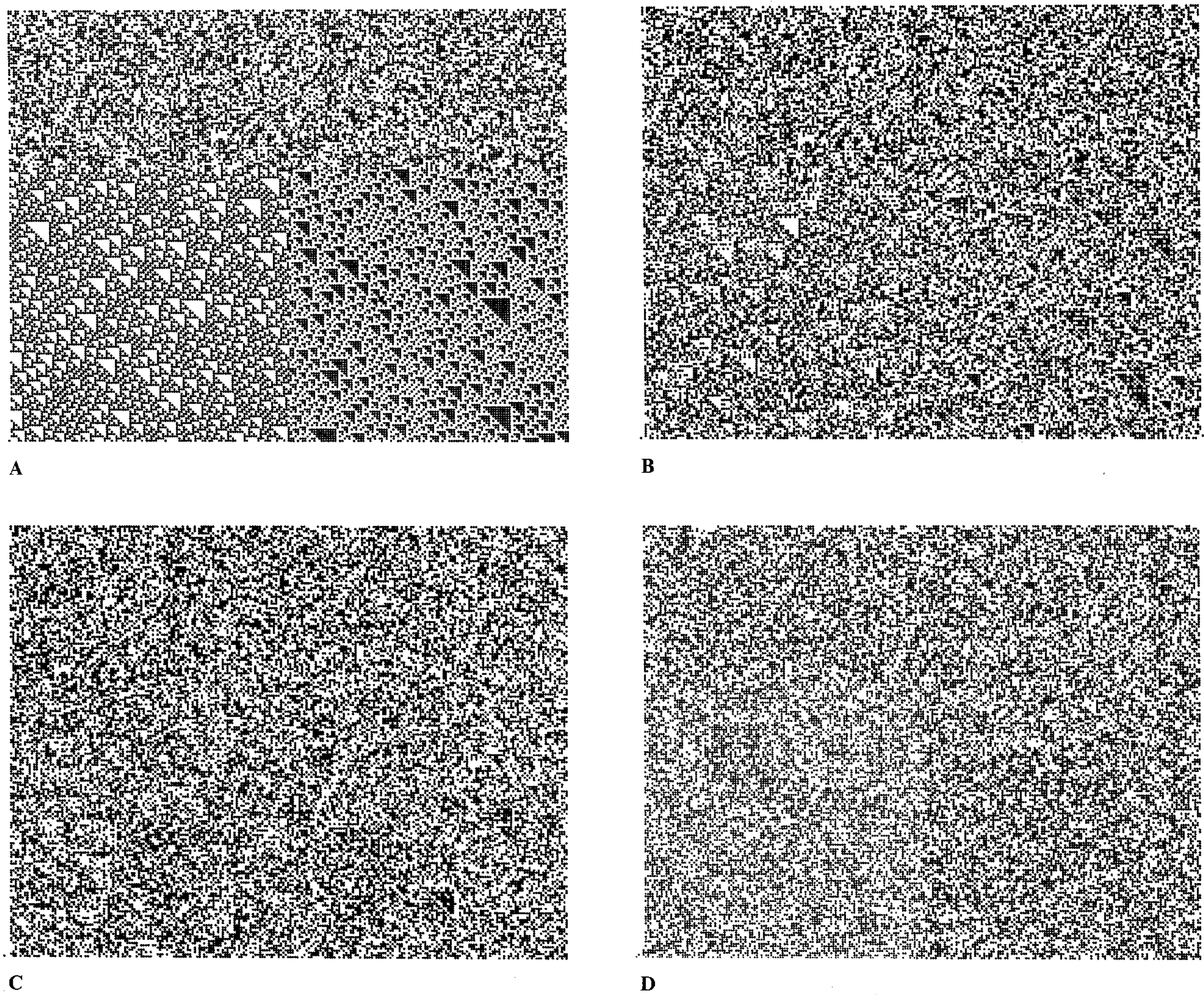

Fig. 13A–D. Similar to Fig. 12, except that a triangular "floater" is three dots generates textures with identical second-order statistics. Here a coherence distance of 3 dots, as shown in **C** still yields discrimination, but the coherence distance of 4 dots yields indistinguishable textures

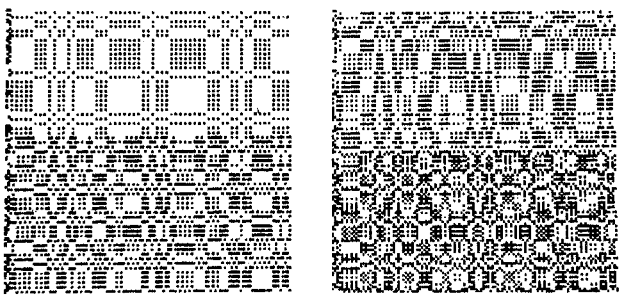

Fig. 14. Depicts in steps how the even iso-third-order texture in Fig. 12B has been generated with 2-dot coherence distance. In the top left image every second row and column of the 2×2 square floater is scanned, and the fourth sample is selected for even parity. In the lower left, one of the remaining positions (out of 4) is scanned by the floater. This is repeated two more times, and is depicted by the top and bottom array of the right image. When this procedure is fully carried out, both for even and odd parities, the left and right bottom textures of Fig. 12B are obtained

Let me note that Gagalowicz (1979) studied two-dimensional stochastic texture pairs whose second-order statistics agreed except for samples at N dot distance. He found discrimination for distances less than seven dots, but at seven dots or further away no texture discrimination resulted. He could study only one-dimensional coherence distances, since in order to study our double-periodic 3×3 case with his method he would have had to solve equations of $2^9=512$ unknowns (and our 4×4 case would have resulted in an equation of $2^{16}=65536$ unknowns).

4. Summary

It has been shown that the preattentive texture discrimination system cannot even process globally second-order statistical parameters, and texture discrimination is based solely on first-order statistical differences of a few *local* conspicuous features called *textons*. If textures are composed of periodically repeated texture elements that are texton-free, then in spite of difference in autocorrelation from stochastic textures containing no periodic elements, no discrimination can be seen. If the periodic texture-elements are texton-rich, then texture discrimination is strong with respect to aperiodic textures. As a matter of fact, whether the texton-rich texture elements are regularly repeated or jittered does not affect the strength of texture discrimination.

The finding that the preattentive visual system cannot process second-order statistical parameters, particularly autocorrelations, and hence Fourier power spectra, is of special interest. In the last decade it became fashionable to use sinusoidal gratings in vision research for contrast detection experiments, and assume that the visual system is able to perform some kind of Fourier analysis. While the attentive visual system can perform complex processing, perhaps even Fourier analysis, it seems to this author that detection of large gratings at threshold is probably a preattentive task. Indeed, the task of deciding whether a "Ganzfeld" becomes something else – not being interested in what pattern the homogeneous field becomes – appears closer to preattentive texture vision than to figure perception by focal attention. If so, the idea of global Fourier analysis in vision is further discredited.

It should be stressed, however, that after the preattentive system extracts the textons from their surround (as in the top left periodic and jittered arrays in Figs. 3 and 4, respectively) their regular or irregular repetition can easily be detected. Whether this regularity is extracted by some second- or higher-order statistical analysis the attentive system might be able to do, or by simply noticing two or more textons of different length (or width) occurring with great density, is an open question. Here it was shown only that the preattentive visual system is unable to extract second-order statistical constraints from dense textures.

It was also shown that in some iso-third-order and iso-second-order texture pairs, composed of dense stochastic texture fields, the range of statistical interaction (coherence distance) does not exceed three or four dots. It appears that it is not the coherence distance per se that can be detected by the preattentive textural system, but rather the fact that for the particular texture pairs beyond the critical coherence distance no elongated blob textons would form in adequate numbers. So, the coherence distance is not a global property of the perceptual system but can be detected only through the density of textons.

In summary, the preattentive perceptual system can instantaneously detect areas (without serial search) in which the textons or their densities differ from surrounding areas. However, this system cannot perceive phase (position) differences between elongated blobs as long as the density of terminators remains constant. In order to appreciate the relative phase between textons (elongated bars and their terminators) that constitute the textural elements, one has to inspect the areas of texton changes with focal attention. Only this second visual system has the "glue" that enables us to tell apart, say, a letter from its mirror image (Julesz, 1981).

As of now, the iso-second-order texture paradigm has been used to search for textons. Here it was shown how an iso-first-order texture paradigm (with periodically repeated micropatterns embedded in randomness) can help to find texton-rich and texton-free micropatterns.

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