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Spatial Nonlinearities in the Instantaneous Perception of Textures with Identical Power Spectra

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Spatial nonlinearities in the instantaneous perception of textures with identical power spectra

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In 1962, Julesz observed that texture pairs with identical second-order statistics but different third- and higher-order statistics were usually not discriminable without scrutiny. Since second-order (dipole) statistics determine the autocorrelation functions and hence the power spectra, this observation also meant that in preattentive perception of texture the phase (position) spectra were ignored. In the last two decades many new classes of texture pairs with identical power spectra have been invented that were not effortlessly discriminable; however, recently (Caelli & Julesz 1978; Caelli *et al.* 1978; Julesz *et al.* 1978) several counterexamples were found. In these texture pairs with identical power spectra some local structures of 'quasi-collinearity', 'corner', 'closure' and 'granularity' yielded strong discrimination. These features can be regarded as the fundamental building blocks of form, that is, the essential nonlinearities of the preattentive perceptual system. Here, it will be shown that these counterexamples are not independent of each other, but can be described by two elementary units: *bars* (line segments) and their *terminators*. Furthermore, the preattentive texture perception system can count the number of terminators but ignores their positions.

1. A quasi-linear conjecture of texture perception

The primary purpose of visual perception is to extract information from the visual environment. This requires irreversible, nonlinear decisions such as the separation of the visual world into figure and ground. As long as a visual subsystem is shown to be linear, no loss of information occurs (i.e. no decision is made), and this subsystem is merely a transmission cable that connects remote processing stages with each other. The only noteworthy property of such a linear cable or fibre bundle is its spatial–temporal spectral characteristics, often shaped to achieve optimal signal transmission in noise.

In 1962, I became interested in the question of whether texture pairs, presented side by side, could be effortlessly discriminated when their second-order statistics were identical, but their third- and higher-order statistics differed (Julesz 1962). In the language of random geometry the *n*th-order statistics is equivalent to the *n*-gon statistics. This is the probability that the *n* vertices of randomly thrown *n*-gons will land on a certain colour combination of the texture. For instance, the statistics that both endpoints of randomly thrown 2-gons (dipoles) would fall on black (or some other specific colour combination) is the second-order or dipole statistics; similarly, the statistics of the three vertices of a triangle falling on a specific colour combination is the third-order or trigon statistics. (A more detailed explanation is given by Julesz (1978).) A texture pair with identical second-order statistics (also called iso-dipole textures), but different third- and higher-order statistics are shown in figure 1. Here one texture consists of identical micropatterns (R's) thrown at random, while the second texture, embedded in one quadrant of the first texture, is composed of micropatterns that are the mirror-images of the micropatterns in the first texture. It has been shown (Julesz *et al.* 1973) that texture pairs composed of mirror-image dual micropatterns are iso-dipole, regardless of the micropattern chosen. As demonstrated in figure 1, such an iso-dipole texture pair cannot be discriminated without scrutiny, in spite of the fact that their third-and higher-order statistics differ. One way to avoid scrutiny by scanning eye-movements, or changes in focal attention, is to present the array for a brief flash (under 200 ms) and such that the boundaries between the texture pair are outside 1° from the centre of fixation.

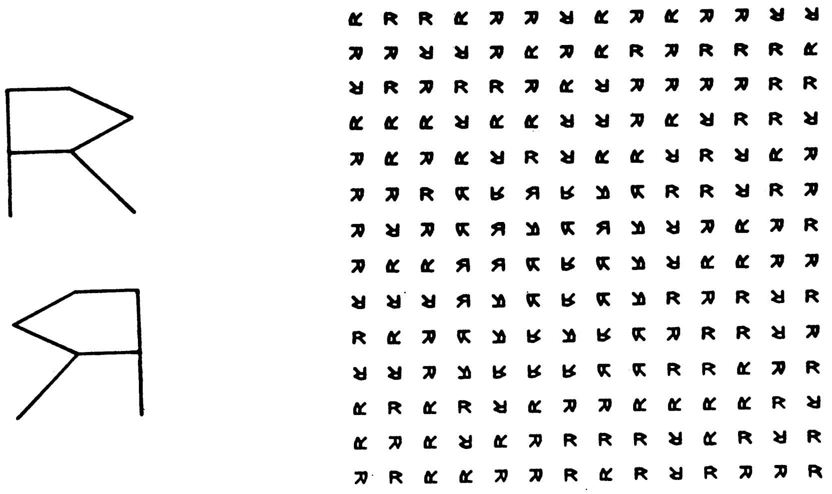

Figure 1. Non-discriminable iso-power-spectrum texture pair generated by the mirror-image dual method of Julesz *et al.* (1973).

Indeed, from 1962 to 1978 many other kinds of iso-dipole textures were generated that could not be effortlessly discriminated (Julesz 1962, 1971, 1975; Julesz *et al.* 1973; Caelli *et al.* 1978; Schatz 1978; Pratt *et al.* 1978). So, my observation that iso-dipole textures are usually not discriminable without scrutiny (Julesz 1962) gained the status of a conjecture.

Such a conjecture is not just a mathematical game. After all, the second-order statistics determine the autocorrelation function (what is more, for black and white textures the dipole statistics is identical to the autocorrelation function). In turn, the Fourier transform of the autocorrelation function is the power spectrum. Therefore, *iso-dipole textures* are also *iso-power-spectra textures*. In the light of this realization the conjecture is equivalent to the statement that 'in preattentive (effortless) perception of textures the phase (spatial position) spectra are ignored'. Thus texture perception is very different from figure perception for which the slightest distortion of phase spectra can render the figure unrecognizable. In a sense, visual texture perception resembles auditory perception, in which the phase information is usually ignored too.

Another iso-power-spectrum texture pair that cannot be effortlessly discriminated is shown in figure 2. The dual micropatterns that are the elements of the two textures, respectively, are depicted in the inset of figure 2, and were constructed according to a method devised by Caelli *et al.* (1978), and explained in figure 3. The inability of the preattentive texture system to perceive the spatial position spectrum is well demonstrated by the non-discriminable texture pair in figure 2. Indeed, one micropattern consists of two rectangles, each containing an X, while in the dual micropattern one rectangle is empty and the other contains two X's. While the dual micropatterns by themselves are perceived as different figures, the corresponding textures cannot be discriminated.

What could we learn about preattentive texture perception if the Julesz conjecture were corroborated? Obviously, it would mean that the preattentive perceptual system operates quasi-linearly, in the sense that only the simplest nonlinear decision is made. This is equivalent to taking the spatial Fourier transform of the input image, and performing one of the simplest nonlinear decisions, the throwing away of the phase spectrum.

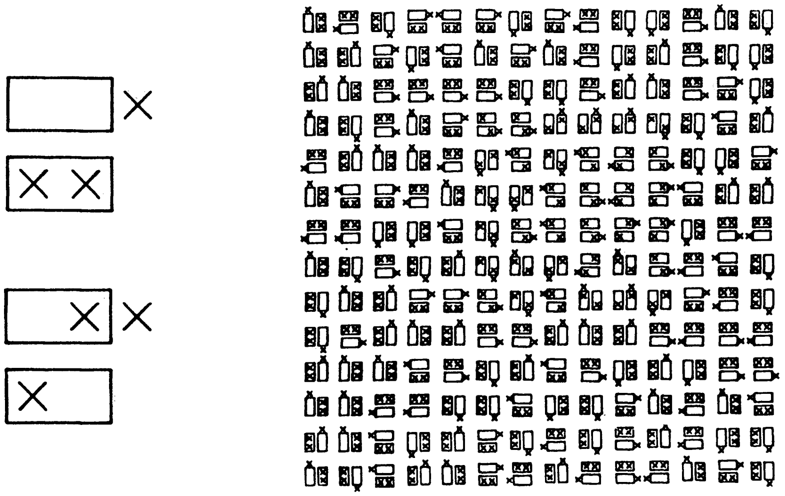

FIGURE 2. Non-discriminable iso-power-spectrum texture pair, demonstrating the insensitivity of texture perception to phase (position) information.

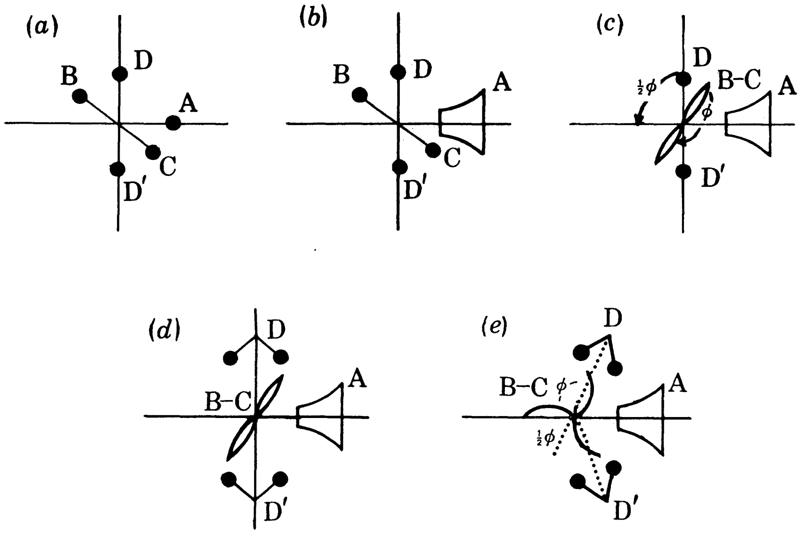

FIGURE 3. Methods for generation of iso-power-spectra textures (e.g. figures 2 and 5). General method for generating iso-dipole micropatterns, seen as a generalization of the four-disk method by four steps. Step (*b*) involves the generalization of disk A to any bilaterally symmetric shape. Step (*c*) converts the disks B and C into any 180° rotation invariant shape. Step (*d*) converts the disks D and D′ into two shapes where each shape is invariant under reflexions on the Y-axis and D′ is the *x*-axis reflection of D. The final step (*e*) demonstrates how B–C can be rotation invariant for 180°/*n* rotations, while D and D′ are symmetric with respect to axes determined by 360°/*n* rotations. (From Caelli *et al.* (1978).)

2. COUNTEREXAMPLES TO THE QUASI-LINEAR TEXTURE CONJECTURE

As we have seen, the quasi-linear texture conjecture is equivalent to assuming that the system makes one of the simplest nonlinear decisions, the ignoring of the phase information. There are many physical systems, from quantum physics to Fourier crystallography, in which the only measureable quantity is the wave power spectrum, and this does not contain any phase information. What is so surprising is the finding that for most textures tried, the visual system appears to behave in this simple fashion.

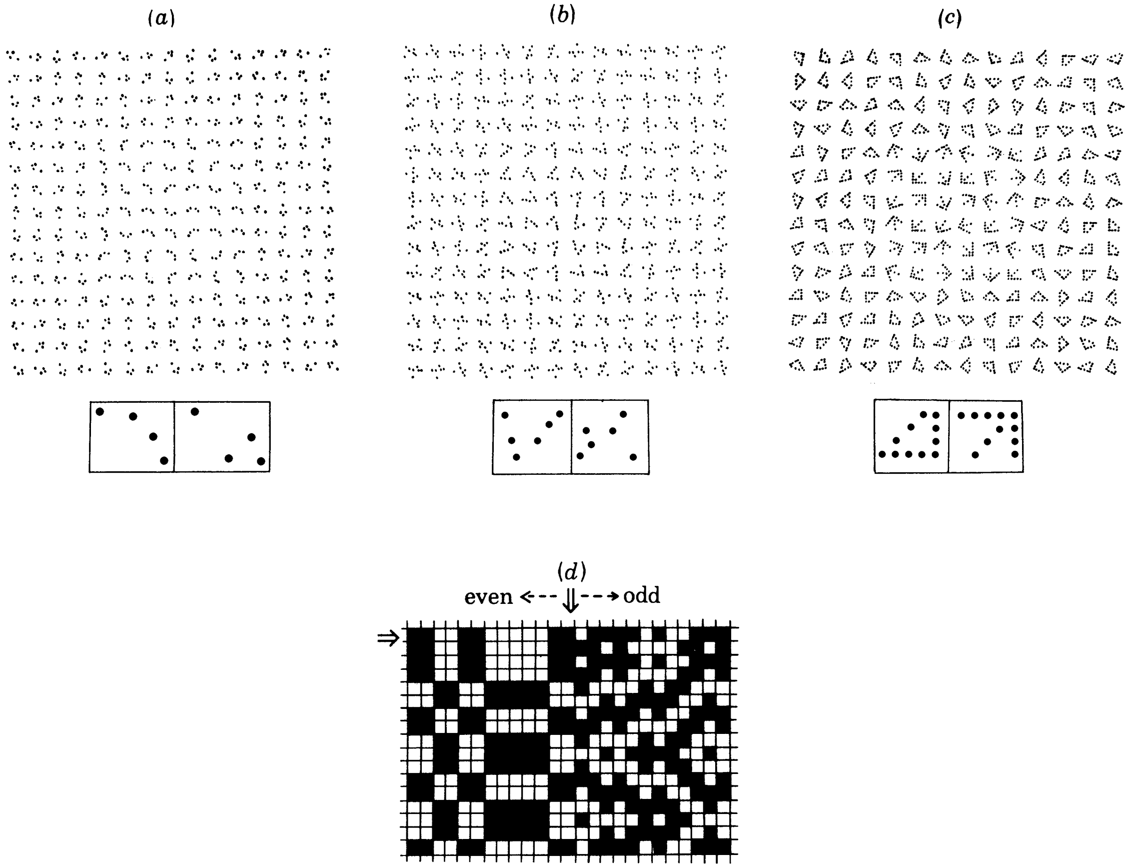

FIGURE 4. Discriminable texture pairs; counterexamples to the iso-power-spectra texture conjecture. Discrimination is based on nonlinear local features of: (*a*) quasi-collinearity, (*b*) corner, (*c*) closure, and (*d*) granularity (blobs). (From Caelli *et al.* (1978) and Julesz *et al.* (1978).)

Obviously, as I pointed out in my earliest articles on texture perception (Julesz 1962, 1965), it is most unlikely that any simple stochastic parameters, such as low-order statistics, could describe the many conspicuous *local* features to which a gamut of cortical analysers are selectively tuned, as revealed by single microelectrode recordings. How could one take seriously a 'Turing imitation game', in which the imitator uses *n*-gons as 'receptive fields' and measures the statistics of their *vertices*, while the real receptive fields in the monkey cortex measure complex properties that exist *inside* the receptive fields. Unfortunately, no mathematician knows how to extend stochastic geometry to more complex statistics than the vertices of *n*-gons. (An important first step was made by Victor & Brodie (1978) who invented texture pairs with iso-Buffon-needle statistics, where the *intersection* of an infinitely long line with the black texture elements is controlled.) Therefore, it is really remarkable that a second-order Turing imitation game (i.e. dipole statistics) mimics human texture perception to the extent that it does.

Recently, several new texture generation methods have been invented that have yielded strongly discriminable iso-power-spectra texture pairs. Discrimination is based on some local conspicuous features such as quasi-collinearity, corner, closure and 'blobs' (granularity) (Caelli & Julesz 1978; Caelli *et al.* 1978; Julesz *et al.* 1978). These counterexamples to the Julesz conjecture are shown in figure 4*a*, *b*, *c* and *d*. The first three are based on the method described in figure 3, while figure 4*d* is not only an iso-dipole counterexample, but is an iso-trigon counterexample, based on a new method devised by Julesz *et al.* (1978). Another method with the use of iso-Buffon-needle textures – that are always iso-dipole textures as well – was invented by Victor & Brodie (1978). This juxtaposes disk textures with ellipsoid textures, and yields stong discrimination. This counterexample is similar to the different local blobs of figure 4*d*.

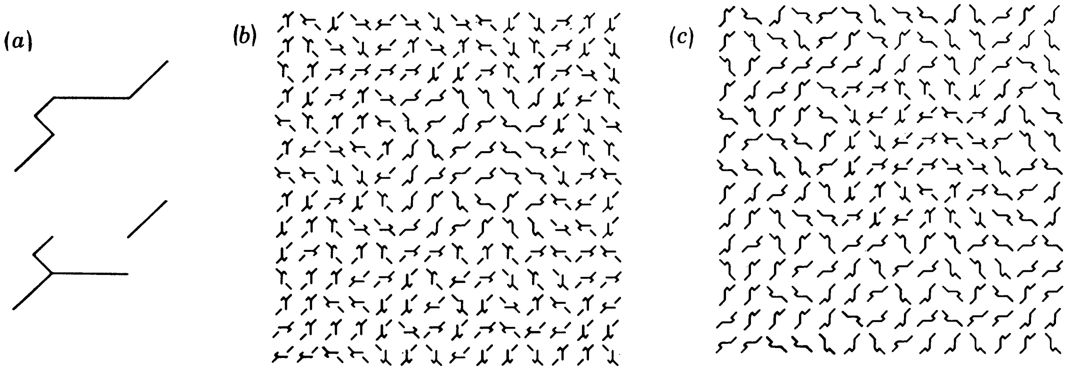

FIGURE 5. Discriminable iso-power-spectra textures based on connectivity.

In figure 5 a new counterexample to the iso-power-spectra texture conjecture is published for the first time. This was constructed by using the method of figure 3*d* and discrimination is based on *connectivity*. Interestingly, discrimination is somewhat different when the unconnected micropatterns form the inside texture, and the connected ones the outside texture, than vice versa. In one case, it is easier to discriminate between the two textures, while in the other it is easier to perceive the location of the boundaries between them.

3. 'Perceptual quarks': bars and their terminators

It was demonstrated in figures 4 and 5 how the counterexample to the iso-power-spectra texture conjecture yielded some of the essential local nonlinearities of the preattentive visual system. The 'blobs' in figure 4*d* are of particular interest, since they are in essence the features to which the simple '*bar detectors*' of Hubel & Wiesel (1962, 1968) are tuned. It is also interesting to note that, contrary to common belief, the 'granularity' of textures (e.g. in figure 4*d*) cannot always be described by the power spectrum, not even by the third-order statistics, but is a fourth-order, or perhaps even a fifth-order property (Julesz *et al.* 1978).

The quasi-collinear counterexample in figure 4*a* is a *line segment*, which in turn is a special case of a thin *bar*. So, figure 4*a*, *d* depicts those conspicuous local features that can be extracted by the elongated receptive fields of simple cortical units found in cat and monkey.

The question arises whether the counterexamples of corner, closure, and connectivity require the postulation of new feature extractor classes, or can be explained by existing ones.

To test independence of the counterexamples, a texture pair consisting of connected (open) and unconnected (closed) micropatterns (see figure 6) was tested by using a 200 ms flash. The micropatterns in the farthest corners of the array were made large enough to be resolved when presented in isolation, and care was taken that micropatterns within a 1° radius around the centre of gaze could not be used as clues. Under these conditions the texture pair in figure 6 could not be discriminated (i.e. observers could not identify the quadrant of different texture better than by chance).

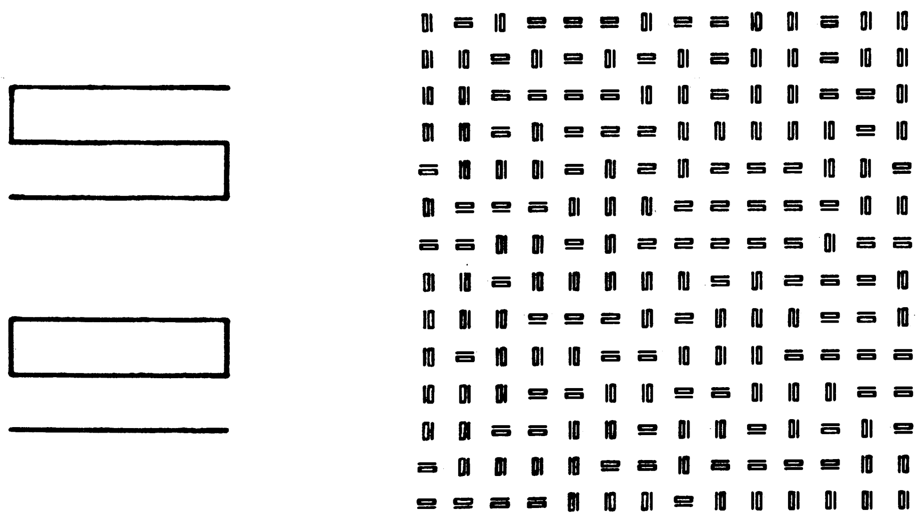

FIGURE 6. Demonstration that textures composed of connected (open) and unconnected (closed) micropatterns, respectively, cannot be effortlessly discriminated, if the number of their *terminators* agrees.

Since the micropattern duals in figure 6 are not iso-dipole, they were chosen to be elongated, to make their dipole statistics more similar. A second texture pair, shown in figure 7, however, permits discrimination. (Instead of a 25% correct guess, which is the chance performance for figure 6, observers of the texture pair in figure 7 guessed the quadrant 72% correctly.)

In figure 6 the dual micropatterns have the same number of line segment terminators (two); however, in figure 7 one micropattern has two terminators, while its partner has three. These experiments clearly show that the preattentive texture system cannot evaluate the exact position of the terminators, only their numbers. In figure perception the 'S'-shaped micropattern is very different from its '10'-shaped partner in figure 6, yet since they both have two terminators, the texture system can only count their numbers, not their exact positions. Discrimination in figure 7 reflects the difference in the terminator number of the micropattern duals. The very strong discrimination (97% correct guesses under tachistoscopic testing) in figure 5 illustrates that even for iso-dipole textures, a large difference in the terminator number of micropattern partners is a decisive parameter.

In a way, the original conjecture – that in texture perception, the phase is ignored – seems to be correct for terminators of bars (line segments). As the texture pair of figure 3 illustrates, even the spatial position of bars (line segments) is not well preserved. However, in many cases, adjacent line segments and blobs trigger wide bar detectors, and thus encode their relative positions to each other.

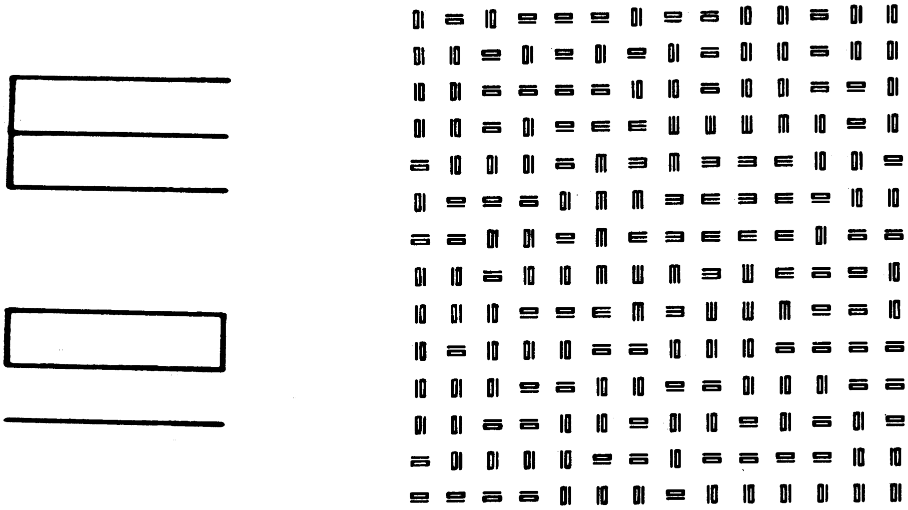

FIGURE 7. Discriminable texture pair, based on the difference of the number of terminators of the micropatterns.

Note that bar (edge, line segment) detectors tuned to specific width, orientation and aspect ratio, and detectors for their terminators are adequate to explain the counterexamples of corner, connectivity and closure. The 'corners' in figure 4*b* differ from their iso-dipole duals, that for the former the quasi-linear dots end in the crossing point (no terminators), while for the latter these dots protrude after the crossing point (two terminators). Similarly, for the closed and open micropattern partners in figure 4*c* and the connected and unconnected ones in figure 5 the difference between the numbers of terminators is three, which explains their strong discriminability.

So, in essence, we can describe the conspicuous local features in iso-power-spectra textures as the combination of bars (line segments) and their terminators. These two 'perceptual quarks', of bars (blobs) and their terminators, are probably the simple and the complex units of the neurophysiologists. Indeed, the simple units extract elongated blobs of specific orientations, widths and aspect ratios, while the complex (hypercomplex) units extract the terminators (corners, ends, gaps) of these blobs. If these bars make up micropatterns such that the bars have the same number, have similar width, orientation and length, and the number of terminators in the micropattern configuration is the same, then the resulting textures are not discriminable.

4. TOWARDS A THEORY OF TEXTURE PERCEPTION

It seems that the perception of line textures is based on some statistics of line segments (with the same orientation and extent) and their terminators, but the exact position of these line segments and terminators is not utilized. Indeed, Julesz *et al.* (1973) stated: 'It might be that the texture discrimination process takes only the first-order statistics of various simple feature extractors that might be segregated according to diameter (and for those with elongated receptive fields, according to width and orientation).' However, they did not know at the time the importance of terminators. It was Marr (1976) that first emphasized the importance of terminators, besides line segments, in the early processing of visual information. His 'primal sketch' model is very reminiscent of the ideas developed here. Nevertheless, there is a crucial difference between Marr's approach and mine. Marr developed his model within the framework of artificial intelligence (a.i.), trying to invent algorithms that are able to perform some well defined perceptual tasks, inspired by the feature extractors of single micro-electrode neurophysiology. On the other hand, the findings reported here were derived by strictly psychophysical methods, and these investigators were often sceptical of the role of the highly local neurophysiological feature extractors in global perceptual phenomena. That the perceptual elements and their further decompositions discovered by myself and my coworkers resemble some of the cortical feature extractors, and some of the feature detectors that Marr has invented, is most gratifying.

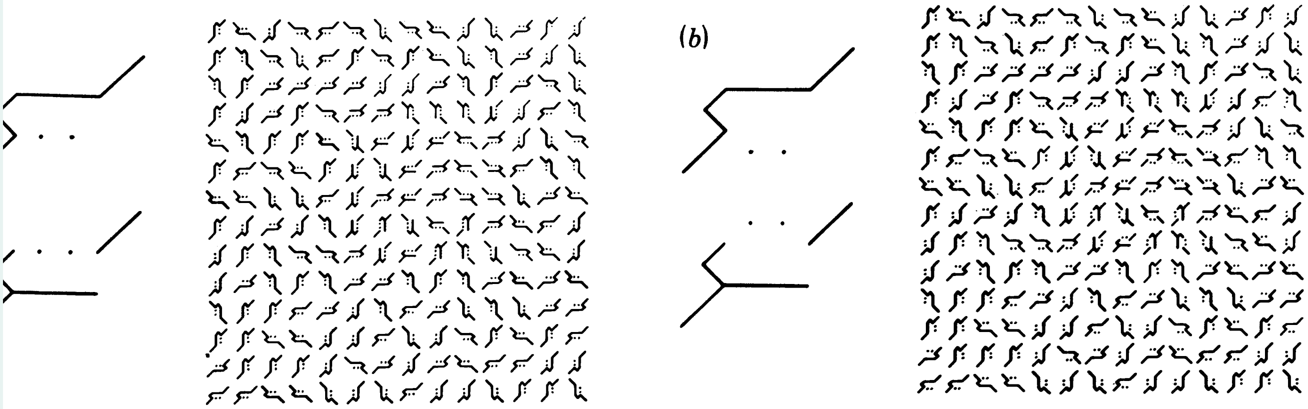

Figure 8. Demonstration of illusory (virtual) line segments acting as: (*a*) connectors (e.g. as real lines); and (*b*) non-connectors (e.g. remaining virtual lines), based on texture discrimination.

Nevertheless, it is most unlikely that the present enterprise of single microelectrode neurophysiology could have revealed the fact that the texture perception system ignores the position of terminators. Similarly, it is unlikely that an a.i. approach could have predicted the discrimination strength as a function of terminator difference. Also, the difference between real and virtual (illusory) line segments cannot be easily guessed, but requires careful psychophysical studies. For instance, we show in the next example how virutal line segments delivered by dots interact with real line segments, by using connectivity as the criterion. Let us take two dots and place them in 'strategic positions' in figure 5, as shown in figure 8*a*. These iso-power-spectra textures are now rendered not discriminable. It appears that when the two dots are collinear with the two corner points of the line segments, they act as connectors, that is as real line segments. However, if the two dots are placed elsewhere, as shown in figure 8*b*, the texture pair is strongly discriminable, which means that the virtual lines defined by the dots are not acting as connectors.

Up to now, we have studied conditions under which textures with iso-power spectra can or cannot be discriminated. On the other hand, as pointed out by Julesz (1962), texture pairs with *different* power spectra often cannot be discriminated. This means that preattentive vision does not utilize the entire second-order statistics, but only a subset of it. Recently, Caelli & Julesz (1979) studied the discriminability of non-iso-dipole textures, composed of pairs of dots (dipoles) as a function of the number (n) of such pairs. When one texture contained dot pairs (dipoles) of a single length and of all possible orientations from 0 to 180°, while the orientation range of the other texture was restricted to a θ interval, as shown in figure 9, a theoretical psychometric function could be derived for discrimination, such that $\ln\theta - \ln(\pi-\theta) \approx \ln n$. As figure 10 shows, data for two observers, and for two dipole lengths, accurately fall on the predicted straight lines. This is one of the few known cases of globality in vision for which an increase in the number of texture elements leads to an improved texture discrimination.

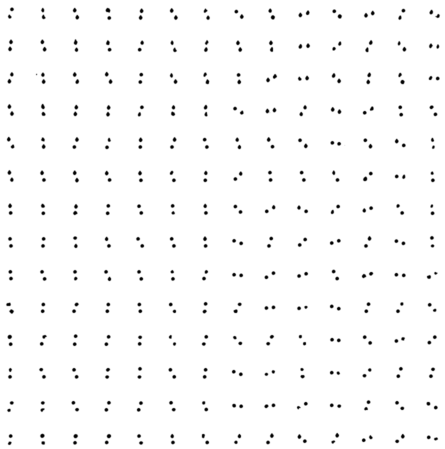

FIGURE 9. Two textures having uniform micropattern dipole orientation distributions. The left texture varies between 70° and 110°, the right between 0° and 180°. (From Caelli & Julesz (1979).)

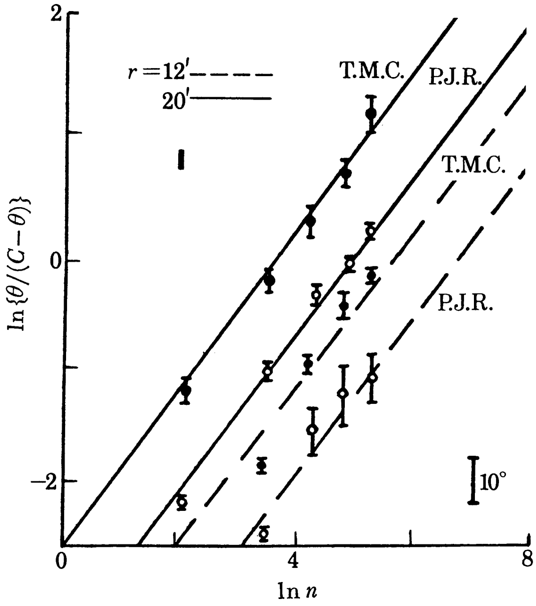

FIGURE 10. Orientation (θ) discrimination on thresholds as a function of number of dipole elements. Lines correspond to theoretical predictions (n, number of micro-patterns; $C = 180°$ range; θ, threshold range for discrimination (degrees); bars represent standard deviations in degrees; r, length of dipole elements in arc minutes). (From Caelli & Julesz (1979).)

However, as is demonstrated in figure 11, if one half field is composed of point pairs of constant length, while the second half field contains greatly varying dipole lengths (with the same mean length as the first half field), no effortless discrimination is experienced. So the texture system is sensitive to dipole orientation changes, but not to changes in dipole length. This finding shows that only a subset of the dipole statistics is utilized. Further psychophysical experiments of this kind are needed to determine the sensitivity of the texture system to the various blob parameter changes as a function of the number of texture elements.

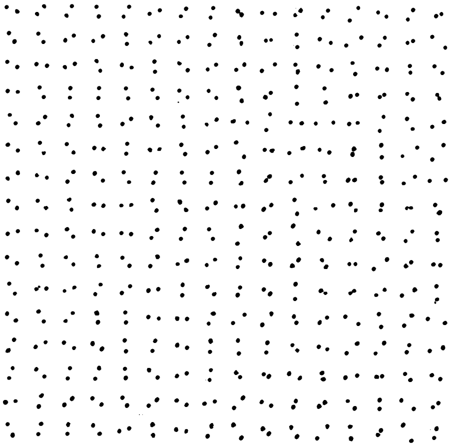

FIGURE 11. Demonstration that only a subset of the dipole statistics has perceptual significance. Left and right textures differ in dipole length variances (left is zero), and no discrimination occurs.

5. TEXTURES AND SPATIAL FREQUENCY CHANNELS

Let us note that the counterexamples to the 1962 conjecture of Julesz, particularly the discriminable textures in figure 4*d*, have strong implications for research with sinusoidal gratings. For instance, Graham & Nachmias (1971) showed, by using the multiple-channel idea of Campbell & Robson (1968), that the detection of the sum of two gratings with 3:1 or higher spatial frequency ratio does not depend on phase. This finding appears to be equivalent to the Julesz conjecture in the Fourier domain; however, it fails for components that fall within a 'critical band' (i.e. that have less than 3:1 spatial frequency ratios).

Thus, these phase-dependent components within the critical bands can account for texture discrimination in some counterexamples. However, in others involving the terminators of bars, the use of gratings in vision research has its limitations. Only gratings that are confined to small subregions have terminators, and, as Julesz & Caelli (1979) have shown, the Fourier phase spectra of figure 4*c* appear equally random for the dual textures with and without terminators.

6. TEXTURE PERCEPTION: THE SECOND VISUAL SYSTEM

In the light of these studies carried out over 17 years by myself and my coworkers, it appears that preattentive texture perception is an early warning system which triggers the attentive perceptual system. If there is some discontinuity in the power spectra of adjacent areas, or there is some conspicuous local change in the orientation, width and aspect ratio of blobs that constitute the texture, or in the number of the terminators of adjacent blobs, the figure perception system is switched on. So the preattentive system can be regarded as the 'ground' perception system, while the attentive system with scrutiny is the 'figure' system. Of course, scrunity requires foveal attention, which in turn is based on scanning eye-movements. On the other hand, to avoid scrutiny, preattentive texture perception is carried out by the peripheral visual system. However, in the periphery, stationary patterns are not well resolved, and they have to move, or be suddenly switched on, to be seen. So texture (or ground) perception can be thought of as the Y-system of transitory patterns pooled in parallel that bring serially into foveal attention the figure system carried out by the stationary, high-resolution X-system, as first discovered by Enroth-Cugell & Robson (1966).

Thus texture perception can be thought of as the second visual system according to most dichotomous subdivisions of the visual system. While the study of this second system is interesting for its own sake, it is my contention that it is the local nonlinear features of this system that are the building blocks of form perception.

7. Conclusion

We have seen how the search for counterexamples to the quasi-linear conjecture led to local conspicuous features of quasi-collinearity, corner, closure, connectivity and blobs which, in turn, could be reduced to bars and their terminators. These psychophysically defined entities ('perceptual quarks') are similar to those that excite the simple and complex feature extractors found in the monkey cortex (Hubel & Wiesel 1968). The importance of bars and their terminators was recognized by Marr (1976) in the framework of a.i. However, he did not distinguish between real and virtual lines (bars), and only after careful psychophysical studies will we know the conditions under which a virtual line segment acts as a real one.

Since the counterexamples of strong discrimination were obtained for textures with identical autocorrelation, they disprove any theory of perception based on autocorrelation. While the textures with identical autocorrelation might consist of dual micropatterns with different autocorrelation (that become identical only when summed over all possible orientations), it should be stressed that the 'figure of merit' defined by the autocorrelation (Uttal 1975) is the same for the micropattern duals in figure 5 in spite of the fact that the textures generated by them yield strong discrimination. So, Uttal's autocorrelation theory cannot explain effortless texture perception.

We have devoted a section to drawing parallels between textures as defined by their statistics and as defined by their distribution over spatial frequency channels. We noted that the essence of the Julesz conjecture in the spatial Fourier domain is that the discrimination of two spatial gratings is independent of phase, if their spatial frequencies differ by a factor of three or more; this is in agreement with the findings of Graham & Nachmias (1971). We also noted that only limited patches of gratings have terminators, and without them no other counterexamples exist to my quasi-linear conjecture. So, the present theory of grating detection is a quasi-linear theory, useful but as trivial as the original texture conjecture.

In summary, the demarcation criterion – to look for effortlessly discriminable textures with identical power spectra – seems to yield the local nonlinear (feature) extractors of the preattentive visual system. If, instead, some other criterion had been used to explain the processing of random-dot textures, these 'perceptual quarks' could have been easily missed. For instance, in a provocative paper, Barlow (1978) studied the discrimination of random-dot arrays with different first-order statistics, using 'efficiency of detection' as a criterion. (He defined this as a ratio between actual performance and the performance of an ideal observer.) He found no evidence for elongated bar detectors in this detection task. This is not surprising, since for most of the random-dot textures tried by myself and my coworkers (Julesz *et al.* 1973; Julesz 1975) no discrimination was found, even when the micropatterns (dot configurations) were selected so that they would differentially stimulate some known neural feature extractors. Only with very atypical dot-textures (shown in figure 4*a*, *b*, *c*) that contained mainly a certain local dot-configuration, were we able to show the presence of *pools* of 'perceptual quarks'. The distance between these quarks (or *textons*, as I started to call them recently), their number and extent are crucial parameters in texture discrimination. Only after the perceptual significance of these parameters is clarified can we hope for a deeper understanding of texture perception. Some of the experiments reported here are the first steps toward this goal.

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