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LOCAL AND GLOBAL VISUAL PROCESSING

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Abstract—The fundamental sinusoidal components of a chequerboard pattern are oriented at 45° to the orientation of the chequerboard edges. Removal of one of the fundamental sinusoids (at +45°) creates a useful pattern for studying the mechanisms of visual analysis. Close up, the pattern appears to be oriented +45°, although there is no global energy at that orientation, implying local analysis. At a distance, the perceived diagonality switches to −45° implying access to global information. Measurements show that contrast thresholds for seeing diagonality at +45° follow closely those for detecting the 5th harmonic component of the pattern, over a wide range of spatial frequencies and luminances. Low pass filtering also causes the pattern to be perceived according to its global energy, provided that the cutoff frequency is set to remove the fifth harmonic. We conclude that, at least for this particular stimulus, the visual system performs a local analysis if the fifth harmonic is visible and a global analysis if not.

Local analysis Global analysis Chequerboards Phase

INTRODUCTION

Sampling may hide from sight the very information it captures. The most familiar example is quantized block portraits, in which the faces portrayed are notoriously difficult to recognize (Harmon and Julesz, 1973). Other examples can be found (Burr *et al.*, 1985, 1986). This is a puzzle since quantal blocking is a sampling process, which preserves information sufficient for recognition. Each element within a sampling block is assigned the average luminance of all pixels in the original portrait, preserving information at low spatial frequencies. Accessibility to this information, and with it recognizability, is restored when the artefacts of the sampling process are removed (Harmon and Julesz, 1973) or rendered less potent (Morrone *et al.*, 1983). The puzzle is compounded by the fact the visual system in man and animal is replete with independent mechanisms, acting early in the analytic process, tuned for orientation and spatial frequency and so working over different scales (see for example Braddick *et al.*, 1978). At one scale at least, information sufficient to recognize a face should be teased out from a blocked portrait. Why then is the information kept by quantal blocking inaccessible?

Masking of components low in spatial frequency by higher components has been suggested (Harmon and Julesz, 1973); but this is doubtful (Morrone *et al.*, 1983). Mismatch of lower scale zero-crossings to those at medium and higher scales has also been proposed (Marr, 1979). Yet another suggestion is that blocking forces vision to analyse locally, or patchwise, within each square, thus missing information at scales outside the confines of the individual blocks, information which we may term global (Braddick *et al.*, 1978; Morrone *et al.*, 1983). But little is known of the conditions under which a partitioned or local analysis is forced upon vision, and less of the relevant mechanisms.

Here we treat a chequerboard as a block averaged sampling of two crossed sinusoids, one at +45° and the other at −45°. When it is seen at a distance at which the higher harmonics are unresolvable, when it is blurred, when it is seen in the periphery, or when it is filtered, the sinusoidal fundamentals become visible. But like the face of Lincoln they are invisible when the chequerboard is seen up close. It then appears as an arrangement of squares with vertical and horizontal edges.

We have created from the chequerboard a stimulus which readily indicates whether global information is accessible. We cancel one of the fundamental harmonics by adding to the pattern the same harmonic in counterphase [Fig. 1(a)]. Globally we have removed one diagonal leaving only the other remaining. When global information is accessible, we should see the residual diagonal at −45°. But when analysis is partitioned square by square, we should see the added diagonal at +45°, as it modulates each square. To map the conditions under which global information is accessible, as signalled by which diagonal is seen, we vary the size and contrast of the modified chequerboard in good light and poor.

METHODS

All stimuli were generated digitally on a PDP-11/60 computer and transferred to a video frame store (Arluna TF4000), which displayed them on a standard video monitor of 12.5 × 12.5 cm, at a mean luminance 50 cd/m^2. The contrast of the video display was varied under computer control by digital attenuation of the video composite signal, after suitable synch separation and DC balancing. For all measurements, the method of adjustment was used. Observers varied the contrast of the stimuli until it was at the appropriate threshold (either for detection, or for seeing a diagonal structure). To avoid response stereotyping, the computer introduced a random contrast offset on each trial. Spatial frequency was varied by varying viewing distance, from 8 cm to 20 m, with the aid of mirrors and an inverted telescope where necessary. For the second set of measurements, the luminance was reduced to 0.05 cd/m^2 with a neutral density filter of 3 log units fitted to appropriate goggles. All observation were monocular with the right (dominant) eye, through a contact lens with 4 mm artificial pupil. DB is emotropic with 6/6 vision, MCM 1.25 D myopic, corrected to 6/6.

The major stimulus under study is shown in Fig. 1(a), and its Fourier transform in Fig. 2. The Fourier transform is like that for a chequerboard, except that one of the fundamental harmonics has been removed. The two large spots in the first and third quadrants of Fig. 2 represent the diagonal at $-45°$ present in Fig. 1; the absence of corresponding spots in the other two quadrants indicates the absence of a companion diagonal at 45°. The other stimuli used for sensitivity measurements were low and high pass filtered versions of Fig. 1(a). The low pass version was simply a sinewave grating oriented at $-45°$, and the high pass version [Fig. 1(b)] produced by removing all energy with less than 3.1 times the fundamental frequency (shown by the dashed circle of Fig. 2). The cutoff frequency was positioned to exclude the fundamental and lower harmonics of the chequerboard, but include the harmonics of frequency $(f_x, 5f_y)$ and $(5f_x, f_y)$, where (f_x, f_y) is the frequency of the fundamental. For convenience these harmonics will be referred to as "the fifth harmonic" throughout this paper.

RESULTS

At close distances, the pattern illustrated in Fig. 1a is clearly seen to have diagonal structure at $+45°$. Some observers see a sinusoidal pattern superimposed on the chequerboard, others see the pattern as corrugated sinusoidally in depth: and sometimes the impressions alternate. At a certain distance from the pattern, the diagonality at $+45°$ gives way to diagonality at $-45°$. At the contrast threshold for transition, interesting impressions sometimes emerge, such as "monocular rivalry" (Campbell *et al.*, 1973) where the real and illusory sinusoids alternate in dominance, and sometimes a plaid pattern with both diagonals simultaneously visible is seen. Seeing the illusory diagonal requires a certain contrast. At close distances the pattern appears indistinguishable from an unfiltered chequerboard at low contrast. We measured the contrast threshold for seeing the illusory diagonal as a function of spatial frequency, and also the frequency threshold for seeing an apparently unfiltered chequerboard at low contrast.

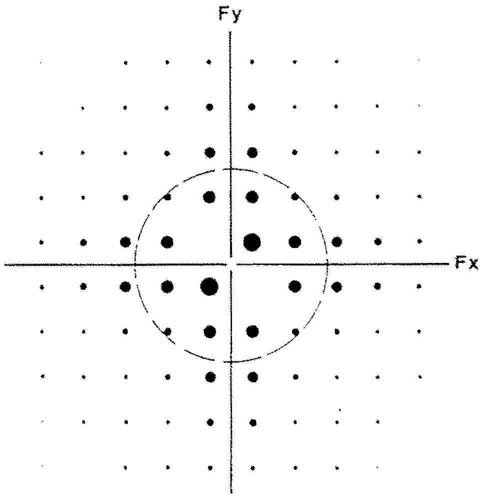

Fig. 2. The Fourier transform of Fig. 1(a). It is like that for a chequerboard, except that one of the fundamental harmonics has been removed. The area of each point indicates the amplitude of each harmonic. For a pattern of infinite extent, the function will localise at discrete frequencies, whose amplitude is give by: $A(nf_x, nf_y) = 4a/(\pi^2 n \cdot m)$, where a is the amplitude of the chequerboard, n and m are odd integers, and f_x and f_y are constants related to the size of the chequerboard, both equal to half the inverse of the check period. The dotted line is the cutoff frequency for producing Fig. 1(b), equal to 3.1 times the frequency of the fundamental (i.e. 3.1 $\sqrt{fx^2 + fy^2}$).

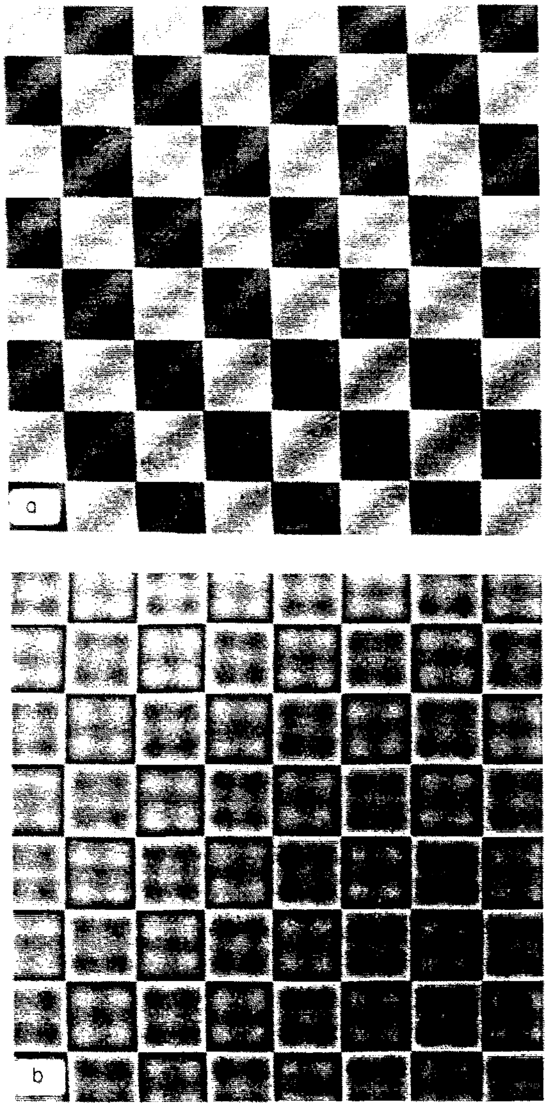

Fig. 1. (a) The major stimulus under study. It was produced by removing one of the two fundamental harmonics from a chequerboard, a process equivalent to adding a diagonal sinusoid of the same orientation and amplitude to that harmonic, but at 180° out of phase. (b) A high pass version of Fig. 1 (a), leaving only those frequencies which fall outside the dotted circle of Fig. 2. To verify some of the results later reported, the reader can conveniently vary the spatial frequency of these patterns by varying viewing distance, and the contrast by back viewing the photograph, and tilting it.

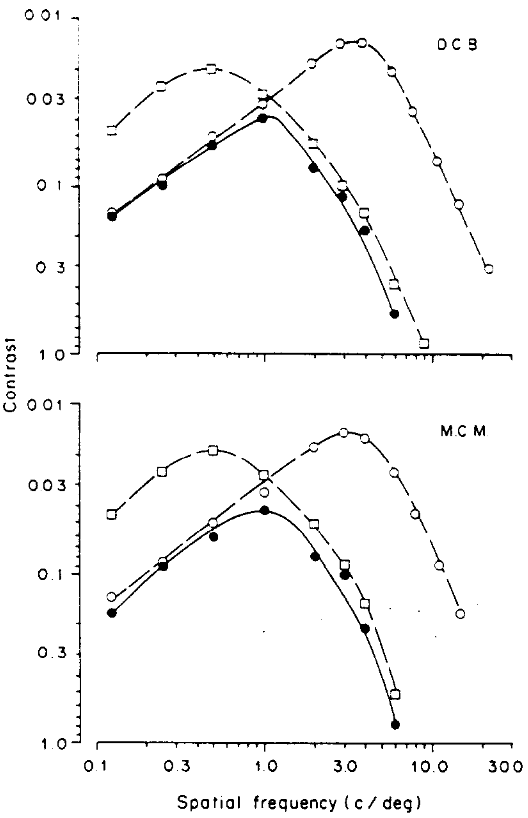

Fig. 3. Filled circles: the minimum contrast required to see positive diagonality in the pattern shown in Fig. 1(a). At lower contrasts observers saw an apparently complete chequerboard at low spatial frequencies (less than 0.9 c/deg for DCB and 0.85 c/deg for MCM), and negative diagonality at high spatial frequencies. The open circles are detection thresholds for seeing the fundamental harmonic alone, and the open squares for seeing a high pass chequerboard comprising the fifth and higher harmonics [Fig. 1(b)]. The contrasts reported are all relative to the original chequerboard, thus accounting for the relative amplitude of the harmonics. The spatial frequency is the spatial frequency of the first harmonic of the chequerboard. All measurements were made at 50 cd/m^2.

The contrast thresholds for seeing the illusory +45° diagonal at various spatial frequencies for the two observers are shown in Fig. 3 (filled circles). At higher contrasts observers saw diagonal structure at +45°. At lower contrasts two perceptual alternatives were possible. At low spatial frequencies observers reported seeing a normal chequerboard, indistinguishable from one which had not been filtered. At higher spatial frequencies, they reported an impression of diagonality at −45°, the orientation of the unfiltered fundamental. The other data points are detection thresholds for various components of the pattern: the fundamental alone (open squares) and for all harmonics greater than or equal to the fifth harmonic (open squares).

Contrast thresholds for seeing the illusory diagonal follow closely those for detection of the fundamental harmonic at low spatial frequencies, and of the higher Fourier harmonics (5th and above) at higher spatial frequencies. The illusory diagonal is best seen at about 1 c/deg, and is never seen at frequencies above 8 c/deg. The viewer can readily verify these results by backing off from Fig. 1. until the positive diagonality of Fig. 1(a) disappears. At this point Fig. 1(b) should be near its detections threshold. Alternatively, view the plate from behind and manipulate the relative back lighting, or simply tilt the pattern to vary contrast by varying the ratio of light reflected from the plate to light transmitted through it. At contrasts insufficient to resolve the high pass pattern, the illusory diagonal also disappears.

To investigate the effect of luminance on the illusion, all measurements were repeated at 0.05 cd/m^2, 3 LUs lower than that used for the previous experiment. The results, shown in Fig 4, are similar in form to those of Fig. 3, but shifted down the frequency scale by a factor of five or so. The thresholds for seeing the illusory sinewave still follow the detection thresholds for the fundamental and for the highpass chequerboard, but all the curves have now been displaced towards the lower spatial frequencies.

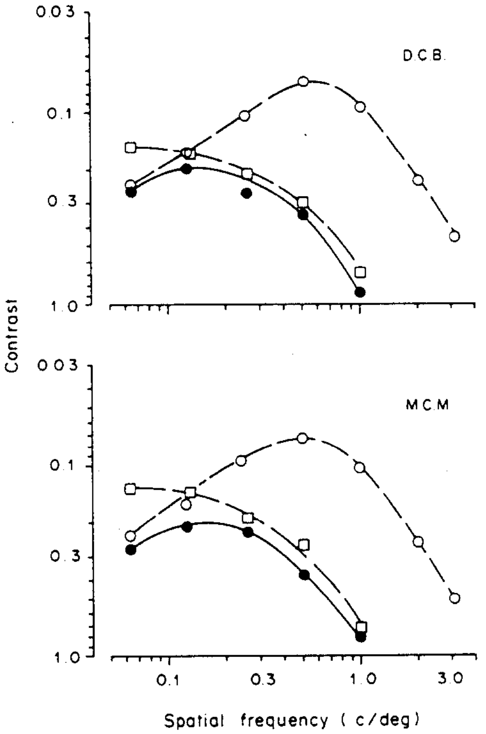

Fig. 4. The same measurements as Fig. 2, collected at 0.05 cd/m^2.

At both luminances, the illusion was never seen unless the contrast of 5th (and higher) harmonics was a few dBs above threshold. Figure 5 provides further support for this. The four pictures are all low pass versions of Fig. 1(a) in which the higher harmonics have been systematically removed. Figure 5(a) has been filtered to include all harmonics up to and including the 9th, Fig. 5(b) the 7th, Fig. 5(c) the 5th and Fig. 5(d) the 3rd. In none of these pictures is the diagonal structure at +45° as strong as in Fig. 1(a), but in all except Fig. 5(d) it can be seen at close distances. Figure 5d, which lacks the 5th and all higher harmonics, never produces the impression of diagonality at +45°.

A further test of the criticality of the fifth harmonic is provided by Fig. 6, showing the modified chequerboard missing its third (6a), fifth (6b), seventh (6c) and ninth (6d) harmonics. The positive diagonal is discernible in all but Fig. 6(b) where the fifth harmonic is missing. Other observations, not reported here in detail, show that it is the phase, not the amplitude of the fifth harmonic, which is critical. When the fifth is shifted 180° in phase only the negative diagonal can be seen.

DISCUSSION

The modified chequerboard can adopt three different configurations. It can be seen as having (1) no diagonality at all: as a normal chequerboard; (2) diagonality at +45°, that of the diagonal subtracted (added in counterphase); or (3) diagonality at −45°, that of the diagonal not cancelled. Near the transition points one appearance may alternate with or rival another, or two may combine.

No diagonality

There is no diagonality at contrasts too low for a diagonal fundamental to be detected, but high enough for the remaining harmonics in combination to be visible. These conditions are met only at close viewing distances, when the spatial frequency of the fundamental is about 1 c/deg or less in good light, or 0.1 c/deg in poor. Neither diagonal is seen when the residual diagonal is below its independent threshold. That is, the modified chequerboard then looks normal; and in this respect resembles the "missing fundamental" of Campbell *et al.*, (1978), and doubtless shares an explanation with it. Campbell *et al.* suggest that the visual system cannot detect the absence of what is missing, and so cannot distinguish the modified from a true square wave. This is true but begs the question as to why square waves, their fundamentals missing or not, are seen as square up close at low contrasts, when the fundamental escapes detection, or at a distance when the higher harmonics are invisible. The rule seems to be that vision assumes the presence of square waveform components in the absence of evidence to the contrary, and knows its operating limits. This rule holds to the limit where pure sine waves of high frequency look square.

Diagonality

In the spatial frequency range where the fundamental can be detected (greater than 1 c/deg in good light or 0.1 c/deg in poor) the modified chequerboard is seen as having clear diagonality, either positive or negative. Negative diagonality indicates access to global information: the diagonal at this orientation is the one not cancelled at a global level (see Fourier transform of Fig. 2). Positive diagonality implies an analysis restricted within the confines of each square for it is there that the local elements of a positive diagonal are present. Our results show that global information is accessible whenever the fundamental in isolation can be resolved but the fifth harmonic cannot. At contrast sufficient for the fifth and higher harmonics in combination to be independently visible (as determined by measurements of them on their own) they force an analysis square-by-square and it is the positive not the negative diagonal that predominates. At smaller image sizes, when the sensitivity to the fundamental is greater than to the combined higher harmonics, it is necessary for a square-by-square analysis that contrast to be a few dBs above the threshold of visibility of the combined fifth and higher harmonics.

No particular range of spatial frequencies as measured at the eye is critical. The boundary from accessibility to inaccessibility of global information varies from 0.2 to 8 c/deg, depending on contrast and luminance. In other words the scale of the pattern sets the scale of what it is that is critical for pattern structure. Nor is contrast gradient critical: the gradient at threshold ranges from very steep (at 8 c/deg, contrast 0.5) to very shallow (at 1 c/deg, contrast 0.1). What is critical is the visibility of the combined fifth and higher harmonics. If these are removed or invisible there is never

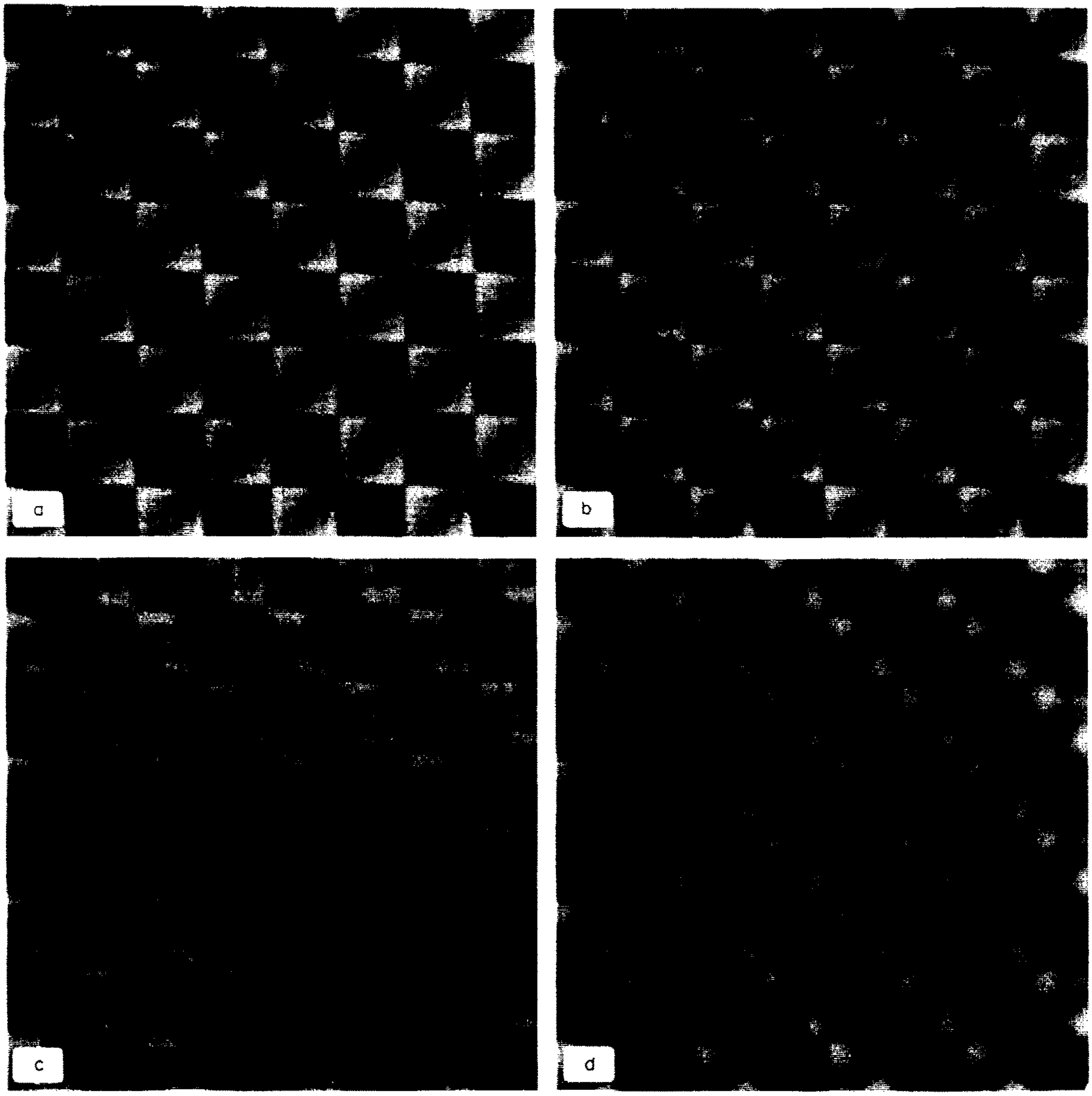

Fig. 5. Low pass versions of the pattern of Fig. 1(a). The cutoff frequencies were 6.5 (a), 5.1 (b), 3.7 (c) and 3.1 (d) times that of the fundamental, so that progressively more higher harmonics were removed. (a) Includes all harmonics up to the "9th harmomonic" [that at $(9f_x, f_y)$ and $(f_x, 9f_y)$], (b) the 7th harmonic (c) the 5th and (d) the 3rd. Without the 5th and higher harmonics, the positive diagonality is never seen.

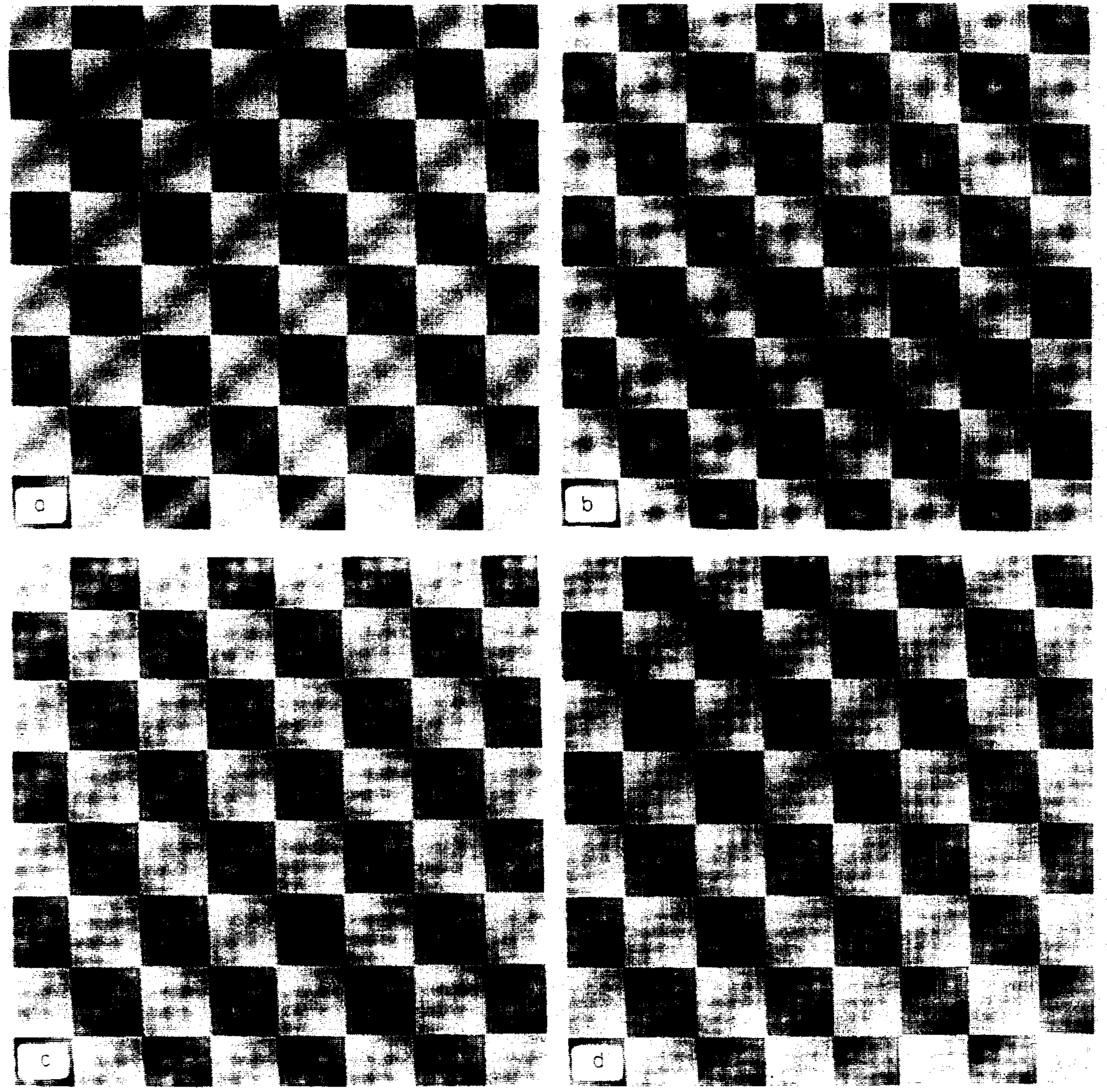

Fig. 6. Notch filtered versions of the pattern of Fig. 1(a). (a) has had the 3rd harmonic $(3f_x, f_y)$, $(f_x, 3f_y)$ removed, (b) the 5th, (c) the 7th and (d) the 9th. Positive diagonality can be seen in all except (b), from which the 5th has been removed.

local analysis, no matter what the scale or the contrast.

It remains far from clear why it is the fifth harmonic, indeed why it is any harmonic at all that decides the appearance of this modified chequerboard. It is unlikely that the fifth itself should have any special status, as many patterns do not even possess a fifth harmonic. More probably, a certain bandwidth of spatial frequency is required. The mechanisms by which a series of harmonics of appropriate phase and frequency cause the visual system to delineate an area within whose borders visual analysis is confined remains a mystery. Further investigations are in progress, looking more closely at the effects of phase on scale of analysis and appearance of pattern.

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