Vision
Image enhancement
Filters

Perception and interpretation of high-pass filtered images

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Abstract. Digital high-pass filtering is used frequently to enhance details in scientific, industrial, and military images. High-pass filtered (HPF) images also are used both to illustrate and test models of visual perception. The visual system appears to interpret HPF images in the context of a multiplicative model of high-frequency reflectance and low-frequency illumination whenever possible. HPF images can be treated as a form of two-dimensional amplitude modulation signals. The low-frequency information, which is coded in the modulation envelope, disappears with the carrier if low-pass filtered. The envelope may be retrieved (demodulated) using one of many possible nonlinear operations followed by a low-pass filter. The compressive nonlinearity of the visual system is shown to suffice for demodulating such images. Simulations show that HPF images cannot be used to reject the hypothesis that illusions and grouping phenomena are due to low-frequency channels.

Subject terms: image understanding; contrast; shape from shading; visual psychophysics.

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1 Introduction

When visually inspecting high-pass filtered (HPF) images, one notes that details perceived in the images can consist of low spatial frequency information substantially below the cutoff frequency of the applied filter. For example, the face image of Fig. 1 has been filtered to remove all information below 14 cycles per picture. If such a HPF image is low-pass filtered below 14 cycles per picture, either digitally or optically, the image will disappear completely. However, the mouth in the middle of the face, constituting information on the order of 2 cycles per picture, is clearly visible. Therefore, the low spatial frequency information must be coded in a manner that can be decoded easily by the visual system when examining the image. This paper describes the coding of the low spatial frequencies in HPF images. It points to the relation between this coded information and the low-frequency content of the nonfiltered scene image and illustrates the feasibility of a decoding mechanism used by the visual system.

Many visual illusions and Gestalt grouping phenomena (the perception of a large shape composed from many small individual elements) have been explained by low-pass filtering of these images by the visual system. If the image of the optical illusion is low-pass filtered and then thresholded at an arbitrarily determined level, the illusory dimensions will appear in the thresholded image where they can be measured.[1] Similarly, in Gestalt grouping images, small dots merging due to low-pass filtering result in a grouping that agrees with the perceptual phenomena. The human perception of these images has been attributed to various low-pass filtering mechanisms such as optical blur,[2] electrical field of induction in the retina,[3] and processing by low-pass filtering channels in the visual cortex.[4]

To disprove the hypothesis[1] that the low spatial frequencies in the images are responsible for the perceptions of these images, Jáñez,[5] Carlson et al.,[6] and Tyler[7] generated HPF versions of the Gestalt grouping images[5] and optical illusions,[6,7] respectively, and showed that the perception remained unaffected despite the complete removal[5] or large reduction[6,7] of the energy of low spatial frequencies in the images. Julesz and Schumer[8] discussed the same concept of low spatial frequency channels as *Gestalt analyzers*. They suggested that some nonlinearity preceding the linear low-pass filtering is essential to explain the perceptual properties. It will be shown here that high-pass filtering does not remove all the low-frequency information; some is coded in the signal envelope and may be retrieved by the nonlinearity of the visual system.

Note that the concept presented here of the nonlinear demodulation of the signal envelope is quite controversial among vision scientists. The results of Henning et al.[9] and Nachmias and Rogowitz[10] have been interpreted by some[11] as inconsistent with such a model. Others insisted that these results should not be interpreted as countering the model[12] and that further experimentation does support the nonlinear model.[13] These issues are addressed further in Sec. 5.

A model of HPF images is presented here as a class of two-dimensional amplitude modulation (2D-AM) signals. From these signals, the visual system can derive the modulation envelope using its nonlinear response characteristics. The modulation envelope also is shown to be associated with the illumination component in many natural scene images. The spatial frequency domain characteristics of simple

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Fig. 1. High-pass image of a girl's face filtered to remove all information below 14 cycles per picture.

patterns are illustrated, and the applicability of the same analysis to more complex images is demonstrated with simulation. Last, a number of examples are presented that suggest that the human visual system tends to interpret HPF images within the framework of the proposed multiplicative imaging model.

2 HPF Images as 2D-AM Signals

Images of natural scenes frequently are described as a multiplication of a high spatial frequency reflectance function with a low spatial frequency luminance function, which may result partly from shading.[14,15] Such a model was explicitly used for developing the homomorphic filtering technique.[16] The same concept recently was applied by Thomas[17] in modeling of spatial frequency discrimination in the visual system. The following illustrates the relationship between an image and its HPF version in the context of this multiplicative model of an image $f(x,y)$:

$$f(x,y)=F_L(x,y)\cdot F_H(x,y) \ , \tag{1}$$

where F_L represents the slowly varying illumination function. The second term, F_H, represents the high-frequency reflectance function. Note that both terms of the equation are non-negative.

Thus, the equation can be rearranged up to a scale factor as:

$$f(x,y)=[1+f_L(x,y)]\cdot[1+f_H(x,y)] \ , \tag{2}$$

where f_L and f_H represent zero mean band-limited stochastic processes, which are the ac components of F_L and F_H, respectively, and $|f_L(x,y)| \leq 1$, $|f_H(x,y)| \leq 1$. Opening the second brackets yields:

$$f(x,y)=[1+f_L(x,y)]+[1+f_L(x,y)]\cdot f_H(x,y) \ . \tag{3}$$

The spatial frequency support of f_H is higher and nonoverlapping with that of f_L. Therefore, high-pass filtering removes the first term, leaving the second term, which can be described as a 2D-AM signal where f_L is the modulation envelope and f_H the carrier. This signal includes negative values and thus a dc term has to be added before the HPF signal can be presented as an image, $s(x,y)$:

$$s(x,y)=1+\frac{1}{2}[1+f_L(x,y)]f_H(x,y)=1+\mathrm{AM} \ . \tag{4}$$

The modulation envelope of an AM signal can be detected using one of many nonlinear operations followed by low-pass filtering. The nonlinearity commonly used in radio applications is the rectification achieved with a diode. The response of the visual system to light patterns is a compressive nonlinear function of the luminance of these patterns. Some researchers[18,19] suggested a logarithmic nonlinearity. The perception of the low-frequency modulation envelope may be attributed to this logarithmic response of the visual system as shown below.

Taking the logarithm of $s(x,y)$ yields:

$$\log[s(x,y)]=\log(1+\mathrm{AM}) \ . \tag{5}$$

If $-1\leq\mathrm{AM}\leq 1$, then the $\log(1+\mathrm{AM})$ can be expressed as a series[20]:

$$\log(1+\mathrm{AM})\approx\mathrm{AM}-\frac{\mathrm{AM}^2}{2}+\frac{\mathrm{AM}^3}{3}-\dots \ . \tag{6}$$

Taking only the first two components,

$$\log(1+\mathrm{AM})\approx\frac{1}{2}[1+f_L(x,y)]f_H(x,y) - \left(\frac{1}{2}\cdot\frac{1}{4}\right)[1+f_L(x,y)]^2\cdot f_H^2(x,y) \ . \tag{7}$$

Since squaring of f_H will rectify this ac signal, it can be rewritten as

$$f_H^2(x,y)=1+g_H(x,y) \ , \tag{8}$$

where g_H is a different zero mean function. Thus,

$$\log(1+\mathrm{AM})\approx\frac{1}{2}(1+f_L)f_H-\frac{1}{8}(1+\underline{2f_L}+f_L^2)(1+g_H) \ , \tag{9}$$

where the underlined term $-\frac{1}{4}f_L$ is the low-frequency demodulated envelope of the AM signal (also called the *distortion product*[12]) and is associated with the illumination function from the original image. This envelope signal may be represented in low spatial frequency channels or mechanisms in the visual system.

The phase inversion (or reversed polarity) of the underlined term is of no consequence in AM radio applications and may have little effect in near-threshold vision experiments in which only the detection of change is required.[10,12] However, it may be important in suprathreshold vision in which phase sensitivity is very high. This problem is addressed further below.

3 Simulations

The following examples help to explain the 2D-AM image structure in the frequency domain. First, we illustrate the concept with simple examples in which the spectral content of the illumination and reflectance does not overlap. The

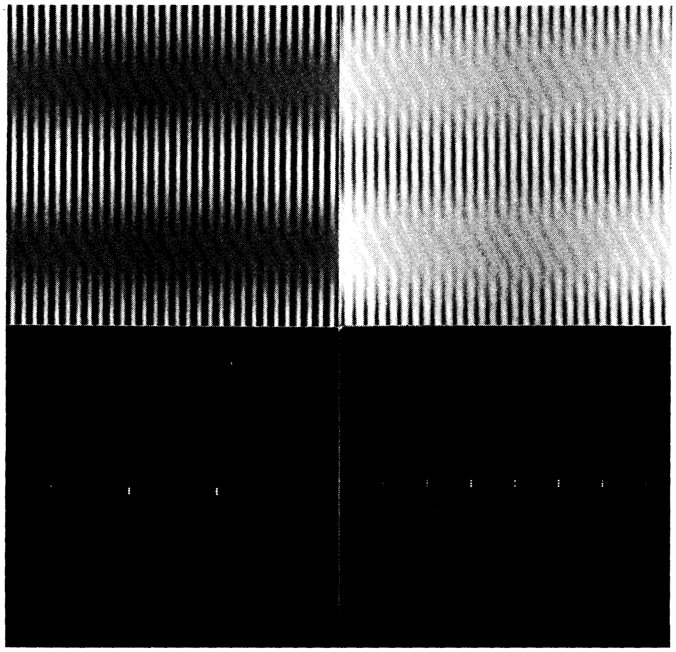


Fig. 2. The orthogonal case of a single-tone 2D-AM image. In this case, the carrier and modulating signals are at 90 deg to each other. (a) Image. (b) Image obtained by taking the logarithm of the image in Fig. 2(a). (c) Spectrum of the image in Fig. 2(a). (d) Spectrum of the logged image; note the clear components at two cycles per picture. In this and any other spectra illustrated here, the center of the image represents the dc location, while the horizontal and vertical spatial frequencies are along the horizontal and vertical axes, respectively.

simulations are used, further, to illustrate that the analysis may be valid for HPF images of natural scenes in which the spectral support of the illumination and the reflectance partially overlap.

3.1 *Simple Signals*

A simple, single-tone, 2D-AM signal may be described in which the carrier and modulating signals are in any two orientations:

$$s(\mathbf{x},\mathbf{y}) = \{[1 + m \cos\omega_o(a\mathbf{x} + b\mathbf{y})] \cos\omega_c(c\mathbf{x} + d\mathbf{y}) + 2\} \ , \tag{10}$$

where m is the modulation index ($m < 1$), ω_c the carrier frequency, and ω_o the frequency of the single-tone modulation envelope. Bold letters are used to emphasize that **x** and **y** are vectors not scalars. In such an image, the envelope information, for example, at $\omega_o = 2$ cycles per picture, is clearly visible [Fig. 2(a)] even though the spectrum contains no energy at this frequency [Fig. 2(c)]. As shown above, this perception can be attributed to the logarithmic response of the visual system. The corresponding peaks are clearly visible in the spectrum [Fig. 2(d)] of the logged image [Fig. 2(b)].

Daugman[21] demonstrated that such single-tone 2D-AM signals represent a special category of images that, despite their apparent easily detected texture differences, have identical zero crossings following convolution with the Laplacian-of-a-Gaussian operator, $\nabla^2 G_\sigma(x,y)$, at any scale. Therefore, such textures could not be discriminated by models using the $\nabla^2 G_\sigma$ zero crossing scheme. Logarithmic compression of the signal will resolve this problem.

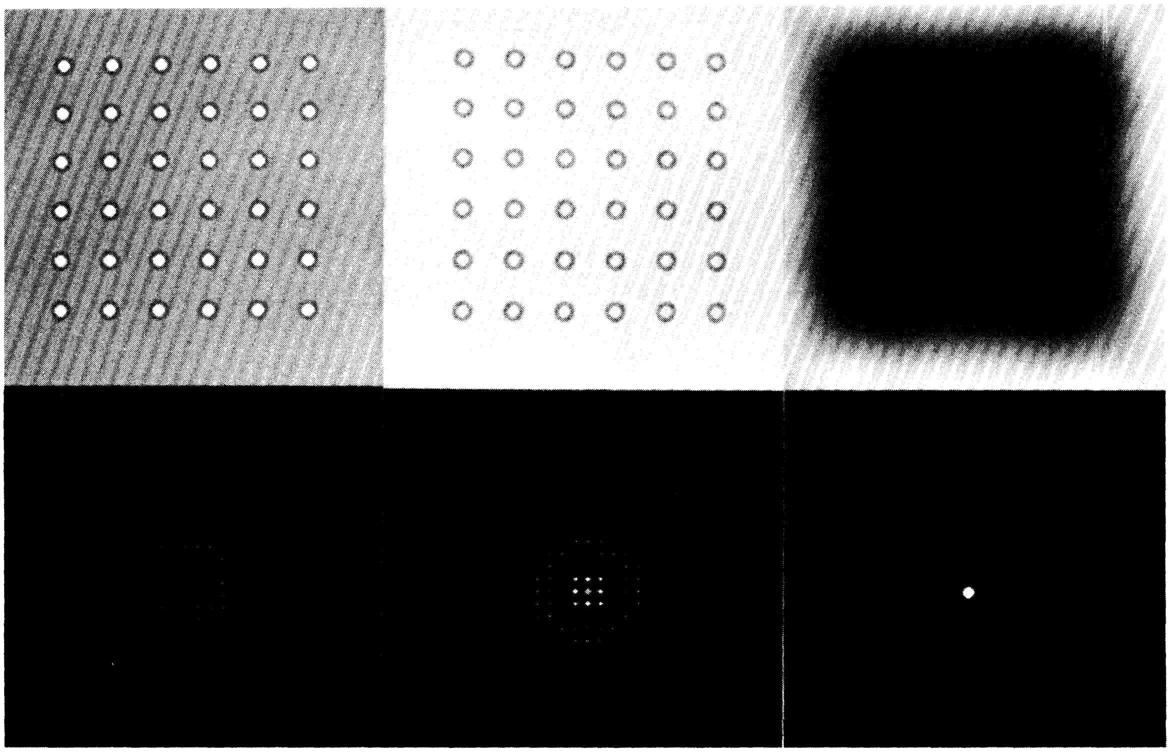
In another example of a 2D-AM signal, the carrier and modulation also can be represented in a polar coordinate system to give the single-tone AM image:

$$s(x,y) = (1 + m \cos\omega_o\theta) \cos\omega_c\rho + 2 \ , \tag{11}$$

where θ and ρ are the polar coordinates. The same demodulation is possible with such images.

More complex images such as those used by Jáñez[5] and Carlson et al.[6] may be described as a sampling of a function that can be analyzed as a pulse amplitude modulation (PAM), a type of AM.[22] The spectrum of a PAM signal differs from conventional AM in that the low frequencies representing the modulating envelope exist in the PAM but are absent in the AM. For this reason, the envelope in PAM can be retrieved by simple low-pass filtering, whereas with AM a nonlinear operation such as rectification or a logarithm is required before the low-pass filtering. The PAM signal or image can be converted into an AM signal either by using an HPF sampling function, e.g., the balanced dots of Carlson et al.,[6] or by high-pass filtering the PAM signal to remove the low spatial frequencies.

Laurimen and Nyman[23] studied image reconstruction from PAM signals and found that reconstruction of the envelope information became more efficient (i.e., required fewer samples per cycle) when the spatial frequency of the signal was increased. At these high frequencies, only the baseband information remains, while the modulated components are



(a) (b) (c)

Fig. 3. The Gestalt perception of a large square built from balanced dots. (a) The original image (top) and its spectrum (bottom). (b) The logged image (top) and its spectrum (bottom); note the appearance of the energy at the low-frequency range. (c) Low-pass filtering of the logged image below five cycles per picture results in a clear image of the large square (top) and spectrum corresponding to the square image (bottom).

severely or completely filtered by the visual system. However, the nonlinearity of the visual response was not considered in their analysis of spatial filtering that could lead to the reconstruction of the sampled images by the visual system.

The balanced dots designed by Carlson et al.[6] constitute an HPF sampling function. The balanced dot is formed from a bright circle surrounded by a dark annulus in which the diameters and brightness levels of the circle and annulus are adjusted so that the average luminance of the dot equals the luminance of the background. Any large shape constructed from such dots [Fig. 3(a), top] can be described as a multiplication of the large-shape function, with the sampling function consisting of a regular grid of balanced dots filling the plane. The spectrum of any such shape [Fig. 3(a), bottom], therefore, will be composed from the spectrum of a single, balanced dot; this latter spectrum is sampled by the Fourier transfer of the bed-of-nails function and is then convolved with the spectrum of the large shape. Thus, the spectrum of the large shape (the square in Fig. 3), a two-dimensional sinc function, is reproduced many times in the frequency domain, yet it is missing from the range of low spatial frequencies. Similar to the case of the single-tone 2D-AM signal, if this image is logged [Fig. 3(b), top], much of the energy in the spectrum is shifted toward the low frequencies, and the sinc function then appears also around the dc position [Fig. 3(b), bottom]. Low-pass filtering of the logged image results in retrieval of the large-square shape [Fig. 3(c)], corresponding to the perception associated with this image. Note that the demodulated square is dark, representing the phase inversion discussed above and below. A similar effect results when an image filtered by Jáñez's[5] high-pass filter is logged.

3.2 *Natural Scenes*

Generalizing these results to natural scene images in which the reflectance and illumination spectrum may overlap is not simple. However, using simulation, we can examine whether other HPF images such as the face in Fig. 1 have similar characteristics, i.e., is it a form of 2D-AM whereby the low spatial frequency information is coded in sidebands and can be retrieved using the logarithmic nonlinearity? The results of such simulations presented in Fig. 4 illustrate that this is the case.

The high-frequency sampling function need not be ordered on a square grid, nor must the sampling elements be symmetrical. The effect of sampling a band-limited function with HPF sampling elements arranged on any grid will be similar in that the spectra will be HPF with the large-figure spectra reproduced and repeated in various places in the frequency domain. Eye charts with high-pass spatial frequency letters[24] or face figures[25] are used to evaluate the visual acuity of adults and infants, respectively. The figures in these charts disappear completely when the threshold of visual acuity is reached, rather than blurring into an indistinguishable "blob." Both types of images are built from

(a) (b) (c)

Fig. 4. Demodulation of the HPF image of the girl. (a) HPF image in which all information below 14 cycles per picture was removed (top) and spectrum of this image (bottom). (b) The log of the image in (a) (top) and spectrum of the logged image (bottom); note the appearance of low-frequency information. (c) Low-pass filtering of the image in (b) to remove all information above 10 cycles per picture results in demodulation of the low-frequency components of the face image.

segments of bright ribbon flanked by two dark ribbons and presented on a gray background. The widths of the bright and dark ribbons are adjusted so that the average brightness is equal to the background. If the length of any ribbon segment is reduced, the figure will resemble a line-drawing caricature. Thus, the concept of the 2D-AM signal can be expanded to explain the organization of low-frequency information in the spatial spectra of line-drawing caricatures as well.

4 Interpretation of HPF Images

It has been suggested that the visual perception of ambiguous 2-D images of 3-D scenes represents a solution chosen by assigning illumination and reflectance values that minimize some cost function.[9] We call this selection of the "most likely solution" the *interpretation* of the image. HPF images, as any other image, always can be interpreted as a trivial case of multiplication of reflectance and illumination functions in which the illumination is uniform and all of the signal is due to the reflectance function. However, it appears that the visual system tends to interpret HPF images in the context of our model, i.e., interprets the modulation envelope as a result of a positive illumination wherever possible. In the case of the HPF image, my conjecture is that such interpretation is selected if the low-frequency information, either directly in the image or demodulated due to the compressive nonlinearity, does not conflict with such a model. Interpretation of shaded surfaces is not always unique even for the original image that was not high-pass filtered; Ramachandran[26] has shown that the interpretation of such images may change with the boundaries or outlines. The shape of the outlines appears to be more compelling than the shading information alone.

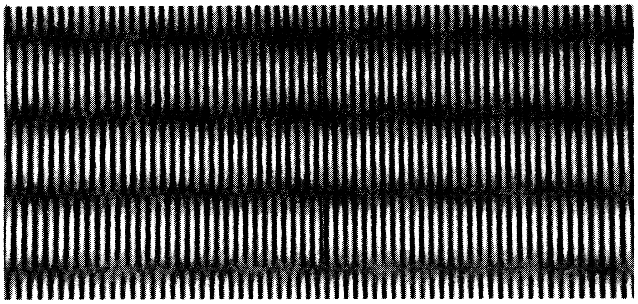
Images can be generated that could not have been obtained by filtering an image composed of positive high-frequency reflectance and low-frequency illumination. My conjecture may be tested with such synthetically generated HPF images. For example, a double-sideband suppressed carrier AM may be used to generate an image in which both the carrier and the modulation envelope get negative and positive values:

$$s(x,y)=m \cdot \sin\omega_o y \cdot \sin\omega_c x \ . \tag{12}$$

After adding a dc term, this signal may be presented as an image [Fig. 5(a)]:

$$s(x,y)=m \cdot \sin\omega_o y \cdot \sin\omega_c x+1 \ . \tag{13}$$

Here the low-frequency, bipolar modulation envelope at ω_o cannot be interpreted as resulting from a positive illumination function. Instead, perception of this image would be consistent with the model of positive low-frequency illumination function. Thus, the visual system interprets this signal [Eq. (13)] as if it were actually [Fig. 5(b)]:



(a) (b)

Fig. 5. Illustration of the tendency to interpret HPF images as resulting from the filtration of an image generated from positive low-frequency illumination and positive high-frequency reflectance. (a) An HPF image with bipolar envelope at two cycles per image [Eq. (13)] is perceived to have a positive envelope of four cycles per image. The difference between this image and the one in (b) [Eq. (14)] is not perceived preattentively and requires careful examination. It is almost impossible to detect this difference if the modulation in both images is in the same orientation as the orientation of the carrier.

$$\hat{s}(x,y) = m \cdot |\sin\omega_o y| \sin\omega_c x + 1 \ . \tag{14}$$

The frequent 180-deg phase shifts that differentiate these two signals [Eqs. (13) and (14)] are largely ignored by the visual system in favor of the positive illumination interpretation. Those phase shifts are even easier to ignore if the modulation envelope and the carrier are in the same direction. Similar responses were recorded from cortical cells. Pollen et al.[27] noted that complex cells stimulated with a compound grating pattern have a strong response component that corresponds to the contrast modulation envelope. Specifically, they showed that for suppressed carrier AM stimulation the cell response is a full-wave rectified version of the bipolar envelope, which may be roughly regarded as a local measure of stimulus contrast.

In the case of suppressed carrier AM, the same interpretation occurs for both low-contrast and high-contrast images. For high-contrast images, the effect of the nonlinearity becomes significant and the demodulated envelope should be considered. Formal application of the logarithm model used above to the signal described in Eq. (13) indicates that, following low-pass filtering, a term at the second harmonics, $2\omega_o$, will be seen followed by a term at $4\omega_o$. If the absolute value of $\sin\omega_o y$ in Eq. (14) is represented by its Fourier series expansion, the image may be expressed as:

$$\hat{s}(x,y) = m\left(\frac{2}{\pi} - \frac{4}{3\pi}\cos 2\omega_o y - \frac{4}{15\pi}\cos 4\omega_o y - \ \dots\right) \sin\omega_c x + 1 \ , \tag{15}$$

which also contains harmonics at $2\omega_o$ and $4\omega_o$; thus, the demodulated low-frequency envelope does not conflict with this interpretation of the signal. However, this is not always the case, as shown below.

The interpretation of a HPF image will change with increased contrast if the demodulated envelopes do not agree with the low-contrast interpretation. Such a change in the perception with contrast is known to occur for gratings composed of the square wave without the fundamental[23]:

$$s(x,y) = 1 + \frac{4m}{\pi}\left(\frac{1}{3}\sin 3\omega_o x + \frac{1}{5}\sin 5\omega_o x + \dots\right) \ . \tag{16}$$

This signal is known[28] to be perceived almost as a square wave (with the fundamental) near threshold, i.e., when $m << 1$. This may be the result of the observer interpreting the signal in the framework of the multiplicative model as a square wave illuminated by an out-of-phase sine wave of the fundamental frequency, i.e.,

$$\begin{aligned}\hat{s}(x,y) &= \left[1 + \frac{4m}{\pi}\left(\sin\omega_o x + \frac{1}{3}\sin 3\omega_o + \frac{1}{5}\sin 5\omega_o x + \dots\right)\right] \\ &\quad \times \left(1 - \frac{4m}{\pi}\sin\omega_o x\right) \qquad (17) \\ &= 1 + \frac{4m}{\pi}\left(\frac{1}{3}\sin 3\omega_o x + \frac{1}{5}\sin 5\omega_o x + \dots\right) + O(m^2) \ ,\end{aligned}$$

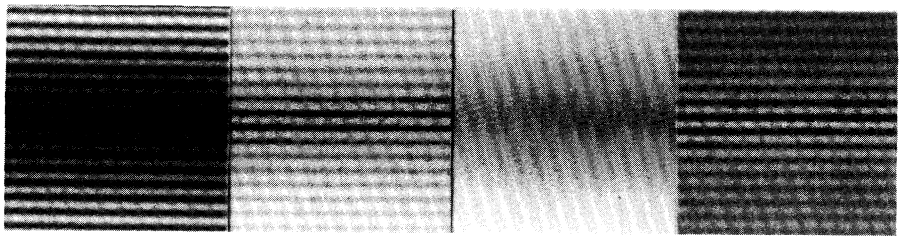
where $O(m^2)$ represents terms of order of m^2 that are negligible for $m << 1$. Regarding a high-contrast case, i.e., $0 << m < 1$, the nonlinearity of the response should be considered. The demodulated envelope then will contain a term of $2\omega_o$, which conflicts with the square wave interpretation but is in agreement with the changed perception of the high-contrast square wave without the fundamental. Testing for the same effect with other wave forms is limited by the need to have wide separation (i.e., more than one octave) between the fundamental and higher harmonics, and yet maintain sufficient amplitude at the higher harmonics, two requirements that contradict each other.

5 Other Issues

The question raised in the introduction regarding the perception of low-frequency information from the HPF versions may be dismissed by noting that the information is available in the space domain. However, the frequency and space domains are equivalent, and any process in either domain can be performed in the other. The fact that the low-frequency information may be demodulated from the image by global processing in the Fourier domain does not mean that such processing actually occurs in the human brain. The purpose of this investigation is to understand the HPF image structure and, ultimately, the perception of that image in relation to the perception of the original prefiltered image.

The argument that the low-frequency information in HPF images is represented in the visual cortex due to the retinotopic mapping of retinal images (and therefore is directly available) only delays the need for an envelope demodulation to a later stage of the visual system. This concept was rejected by the early experiments of Burton[18] that demonstrated the detection of a beat-like pattern produced by two-sine-wave gratings, even when these gratings were too high in frequency to be detected and thus did not exist in the cortical retinotopic mapping.

Although the results of Nachmias and Rogowitz[10] and Nachmias[12] have been interpreted by some[11] as counter examples for the early or late nonlinearity models, respectively, they do not contradict the model for visual perception



(a) (b) (c) (d)

Fig. 6. The inversion of phase between the illumination component and the envelope of the contrast detected by high-frequency mechanism. (a) An image generated by a low-frequency illumination multiplying a high-frequency reflectance. (b) The same image after logarithmic compression transformation. (c) The local luminance mean calculated by low-pass filtering the image in (b). (d) The band-limited local contrast of the image in (b) calculated for a mechanism tuned to the high spatial frequency of the reflectance pattern. Note that the contrast envelope is inverted in phase to the original illumination pattern.

of HPF images postulated here. In fact, Nachmias specifically pointed out: "These results have no obvious bearing on the question of whether point nonlinearities actually exist in the human visual system." [12]

Derrington and Henning[29] rejected the distortion product as a cause of the masking they measured. They did not find a masking peak near the frequency of the distortion products (for the lower angular separation cases). However, for such cases, the masking by the high-contrast, three cycles per degree pattern may have been larger than the effect of the distortion product. Logvinenko[13] recently directly tested the distortion product hypothesis and distinguished it from the hypothesis of Derrington and Badcock[30] that the patterns are detected by local contrast discrimination. He measured contrast thresholds for a two-sine-wave compound grating under systematic reciprocal variation of the amplitude of each frequency component. His results supported the early nonlinearity hypothesis. He suggested that, depending on the experimental paradigm and the stimuli, either the distortion product or the spatial-beat pattern may account for the detection of the patterns.

Carlson et al.[6] considered the possibility that a log transformation of retinal intensity could account for the perception of the illusions in balanced dot images. They rejected this possibility after experiments in which they modified the intensities to pre-emphasize the image in a way that should inverse the logarithmic retinal response, which resulted in no change in the perception of the illusion. However, this experiment may reject only the simple model in which the compressive nonlinearity is restricted to the first element in a cascade of otherwise linear elements. In the visual system, a more likely model will include distributed nonlinearities. Although the total system response to uniform illumination may be measured as logarithmic, the system as a whole is not commutative and cannot be replaced with a cascade of a nonlinear and a linear element. Such a late nonlinearity recently was described by Derrington[31] and discussed further by Nachmias[12] and Logvinenko.[13]

HPF images appear surprisingly familiar and recognizable even though we know of no such appearance in nature. It is tempting to speculate that this familiarity may result from the existence of HPF images in some internal representation in the visual system. Indeed, in the context of spatial frequency channel models, the representation of images in channels centered at higher frequencies should be a form of HPF images. The representation of a natural scene as described in Eq. (2) may be analyzed using the definition of band-limited local contrast proposed by Peli.[32] By means of the logarithmic compressive nonlinearity followed with this definition, we find in addition that the contrast envelope is inverted in phase to the original illumination-derived amplitude envelope. For the compressed image,

$$\log s(x,y) = \log[1 + f_L(x,y)] + \log[1 + f_H(x,y)] \ . \tag{18}$$

If we approximate each term using only the first-order term in the Taylor expansion, the contrast at the band centered at f_H can be expressed at each point as the ratio of the bandpass-filtered signal to the log local luminance mean:

$$C_{f_H}(x,y) \approx \frac{f_H}{1 + f_L} \approx f_H(1 - f_L) \ , \tag{19}$$

which illustrates the inversion of the phase of the contrast envelope compared with the illumination. The effect calculated without approximations is illustrated in Fig. 6.

Thus, the inverse phase relations between the decoded envelope of the HPF image and the original illumination may be familiar and raise no conflict in the perception and interpretation of such images. Hayes et al.[33] found that bandpass-filtered face images containing high spatial frequencies were equally well recognized whether presented as positive or negative. However, recognition of images containing a low-frequency component was much poorer for negative than for positive polarity. Hayes and Ross[34] recently showed that the recognition of line drawings of faces is not affected by inversion of polarity. However, if the line drawings are augmented with shadows (adding direct illumination, low spatial frequency information), the recognition of the polarity-inversed drawings is reduced significantly. In this case, the decoded envelope conflicts with the direct low-frequency representation, and that conflict may affect recognition.

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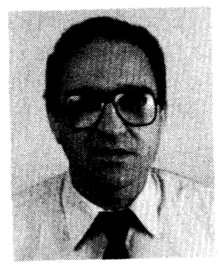

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