Visual Preprocessing:

First- and Second-Order Processes in the Perception of Motion and Texture

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Abstract

The development of a theory of human 2nd-order motion perception and its application to the discrimination of texture slant is outlined by means of a series of examples and demonstrations. The computational algorithms for deriving the direction of left-right motion from a sequence of images are equivalent to the algorithms for deriving the direction of slant (e.g., from top left to bottom right or top right to bottom left) in a single 2D image. There is a broad range of phenomena for which Fourier analysis of the image plus a few simple rules gives a good account of human perception. The problem with this *1st-order* analysis is that there exists a broad class of "microbalanced" stimuli in which the motion or slant is completely obvious to human subjects but is invisible to 1st-order analysis (Chubb & Sperling, 1988). Microbalanced stimuli require *2nd-order* analysis, which consists of nonlinear preprocessing (spatiotemporal filtering followed by rectification of the input signal) before standard motion or slant analysis. To determine whether the 2nd-order rectification is halfwave or fullwave, two special microbalanced stimulus types are constructed: "halfwave stimuli" whose motion (or texture slant) is interpretable only by a halfwave rectifying system but not by fullwave or a 1st-order (Fourier) analysis and "fullwave stimuli" which are interpretable only after fullwave rectification. Such experiments show that 2nd-order texture-slant perception utilizes both halfwave and fullwave processes; 2nd-order motion-direction discrimination depends predominantly on fullwave rectification; and 2nd-order spatial interactions such as lateral contrast-contrast inhibition and 2nd-order Mach bands are exclusively fullwave.

1st-Order Motion and Texture

The stimulus domain. A basic motion stimulus, a vertical gray line that moves from left to right in successive frames, is shown in Fig. 1a. The concern here is only with monochromatic stimuli, so the full description of such a two-dimensional (2D) stimulus is the specification of luminance $l(x,y,t)$ at every point in space x,y and time t. A dynamic 2D stimulus is defined within a cube in x,y,t. Under ordinary illumination, vision is largely independent of the absolute level of luminance; it is more useful to describe stimuli in terms of contrast, the local luminance divided by the average luminance l_0 of the display: $c(x,y,t)=l(x,y,t)/l_0$.

Coordinates: motion (x,t) versus texture (x,y). Because the moving bar of Fig. 1a does not vary in the vertical direction, the vertical coordinate can be omitted. An x,t cross-section of the 2D

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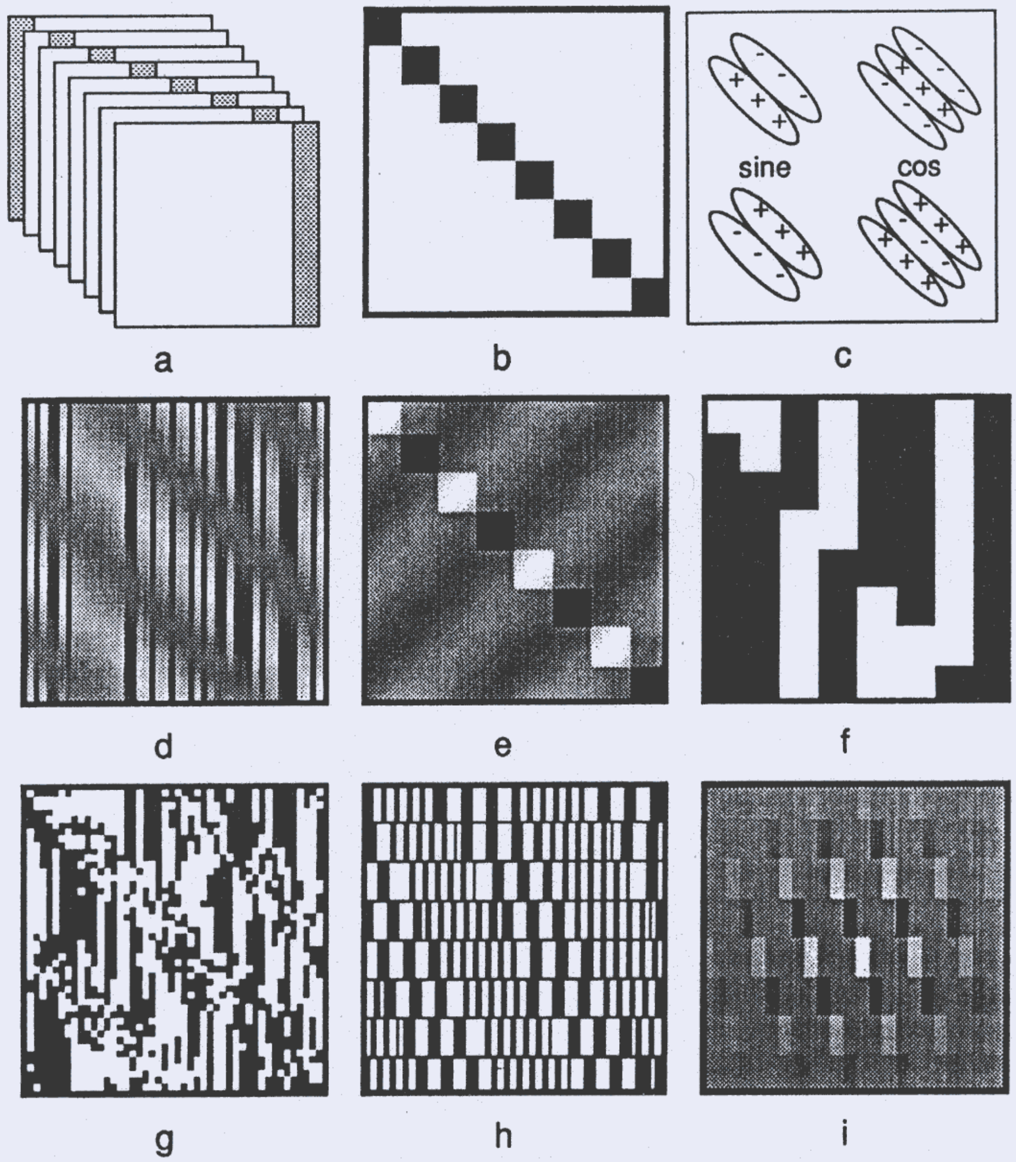


Figure 1. Motion/texture stimuli. (a) Eight frames of a dark vertical bar moving from left to right. (b) Cross-section of (a). The abscissa is horizontal space, x; the ordinate is time t. Panel b is an x,t representation of a moving bar; equivalently, it is an x,y representation of a slanted line. (c) Four receptive fields of Hubel-Weisel simple cells or, equivalently, linear filters in x,y (or x,t). Areas of positive response are indicated by + , areas of negative response by - . (d-i) x,t representations of moving stimuli or, equivalently, x,y textures. The abscissa is x, the ordinate is t (motion) or y (texture); d,f,g,h are microbalanced. (d) Left-to-right movement of contrast-modulation of static noise. (e) Contrast-alternating moving bar. The primary Fourier motion component (upper right to lower left) is lightly superimposed on the actual pattern. (f) Left-to-right-moving pixel flip. (g) Left-to-right-moving rate-modulation of pixel flips. (h) A texture quilt. The eight rows represent eight consecutive frames. (i) Left-to-right-moving contrast-alternating grating within a Gaussian x,t window. Fourier components slant from upper-right to lower left; fullwave components slant from upper left to lower right; halfwave components are ambiguous.

space-time stimulus, as in Fig. 1b, fully specifies the stimulus. Motion to the right is represented along a diagonal from upper left to lower right. Motion to the left would be represented by the opposite slant (from upper right to lower left). We can see at once that the motion-direction problem of determining whether the the bar moves from left-to-right or from right-to-left in x,t is formally equivalent to the texture-slant problem of determining whether the little squares form a pattern that slants from upper left to lower right or *vice versa*.

Receptive fields, Gabor filters. It is easy to solve the texture slant problem in terms of receptive fields of neurons in the visual cortex — the "simple cells" of Hubel and Wiesel (1968). The receptive fields of four such cells are shown in Fig. 1c: line detectors (labeled cos) and and edge detectors (labeled sine). When a slanted pattern (as in Fig. 1b) is superimposed on such a receptive field, the pattern produces a large response. The response may be either positive or negative, depending on whether the squares are dark or light and on whether they align with + or - regions. Neurons tend not to communicate negative signals well--if at all--so the normal configuration in the nervous system is a neural pair. For example, for line detectors, a plus-center neuron would signal a positive response for a light line in its center, or a dark line in the adjacent side lobes. A minus-center line-detector (-cos) has the plus and minus signs reversed, and responds to dark lines in its center (Fig. 1c, bottom). A push-pull pair (Sperling, 1970, p. 529ff) of neurons with oppositely signed receptive fields can convey a full range of both signs of contrast, and has the advantage of being silent when there is zero input.

A push-pull pair of oppositely signed neurons can be regarded, to a first approximation, as being equivalent to a linear filter that conveys positive and negative values equally well in its output. Such filters for representing visual sensory neurons are often modeled as Gabor functions (Gaussian windowed sine waves, e.g., Olzak and Thomas, 1986).

Either sine or cosine filters could be used to distinguish between +45 and -45 degree slants. To determine whether the line is slanted +45 or -45 degrees, the outputs of filters slanted +45 and -45 degrees are compared. Because the filter output might be either positive or negative, the comparison is between the *magnitude* or square of the outputs, not between the signed outputs.

1st-order perception: Quadrature pairs, directional energy, standard motion analysis. When the exact location of the line relative to the receptive field is unknown, the problem is a little more complicated. One scheme would be to consider only the +45 deg and -45 deg filters with the largest magnitude outputs and compare their outputs. Another scheme might be to consider the total stimulus power at the +45 and -45 deg slants. A similar problem occurs in the detection of radar signals (Weinstein and Zubakov, 1962), and the optimum solution is to sum the squared outputs of a sine and a cosine filter. Such a pair of sine and cosine filters is a *quadrature pair* and it computes the total "energy" of the input in its direction of slant. Looking at all slant directions, and finding the quadrature pair with the greatest output, is a solution to the problem of finding the dominant slant of a texture (Knutsson and Granlund, 1983).

In motion, directional energy is computed in the x,t domain instead of in the x,y domain, as in texture. In the realm of motion, van Santen and Sperling (1985) proved that the three then-current computational theories of motion-direction perception all, in effect, made a comparison between quadrature pairs: (1) the widely accepted Reichardt model (Reichardt, 1957; van Santen & Sperling, 1984), (2) the motion-energy model (Adelson and Bergen, 1985), and (3) a reasonable elaboration of the Watson-Ahumada (1985) motion filter.

There is a broad range of phenomena for which Fourier analysis of the image plus a few simple rules gives a good account of human motion and texture perception (e.g., Watson, Ahumada & Farrell, 1986; Caelli, 1982). Van Santen and Sperling (1984) tested and verified three incisive, counter-intuitive predictions made by the Reichardt model about complex motion stimuli. Thus, a directional energy theory is particularly well established in motion perception. We shall refer to this entire class of theories in various contexts as *standard motion analysis* or as *1st-order motion analysis* or as a *directional energy* computation.

2nd-Order Motion and Texture

2nd-order stimuli. There are two obvious problems with standard motion analysis. The first is exemplified by the stimulus shown in Fig. 1d. This is a contrast modulated random noise pattern. The random noise is a stationary "carrier;" only the modulation moves. The x,t motion of this type of stimulus is invisible to standard motion analysis, but we have yet to find an observer who does not perceive its obvious apparent motion. Similarly, in the x,t version of the stimulus (Fig. 1d), the upper-left to lower-right slant is completely obvious, but it cannot be detected by the Gabor filters or Hubel-Wiesel simple cells shown in Fig. 1c.

The second problem with standard motion analysis is exposed by a stimulus (Fig. 1e) in which the bars in successive frames alternate between black and white (cf. Anstis, 1970). Here the slant is obviously from upper left to lower right, but the dominant Fourier component is from upper right to lower left (indicated by slight shading in Fig. 1e). Normally, observers see the x,t (moving) version of the stimulus as moving to the right. However, in peripheral vision or when viewed from far away, the reversed motion is easily seen (Chubb and Sperling, 1989).

The above examples indicate that there must be another motion computation in addition to standard motion analysis, and another spatial slant computation in addition to a quadrature-based slant analysis. Chubb and Sperling (1988) pointed out that simple rectification (e.g., absolute value or squaring) of local stimulus *contrast* prior to standard motion analysis is a logical candidate for the second computation, and they called perception based on such a computation *2nd-order* perception. Simple rectification would expose the latent x,t motion or x,y slant in the stimuli of Fig. 1d and 1e to standard motion analysis (Fig. 2b versus Fig. 2a). But rectification fails with binary-intensity stimuli such as Fig. 1f and 1g because it converts them into a completely uniform field.

Driftbalanced and microbalanced stimuli. Stimuli 1d,f,g,h are all random stimuli, and they have the property of being driftbalanced and microbalanced (Chubb and Sperling, 1988, 1991). Driftbalanced means that the expected power in any mirror-opposite directions ($+\phi$, $-\phi$) is exactly equal. Summed over the area of a driftbalanced stimulus, a field of Reichardt motion detectors will have zero expected output. Stimuli 1d,f,g,h have the further property of being *microbalanced*: that is, they remain driftbalanced when viewed through any space-time separable window. Microbalanced stimuli are particularly useful for neurophysiological investigations where the receptive field (window) of a neuron is not known. The expected output of every individual Reichardt detector is zero for microbalanced stimuli. Nevertheless, no sighted observer has yet failed to see the motion in the stimuli of Fig. 1d,f,g,h.

Texture quilts and texture grabbers. To expose the motion of stimuli of Figs. 1f and 1g to standard motion analysis, an obvious embellishment to simple rectification is temporal differentiation or temporal bandpass filtering (Fig. 2c). The stimulus of Fig. 1h (Chubb & Sperling, 1991) provides a counterexample to this too-simplistic line of improvement. It is called a *texture*

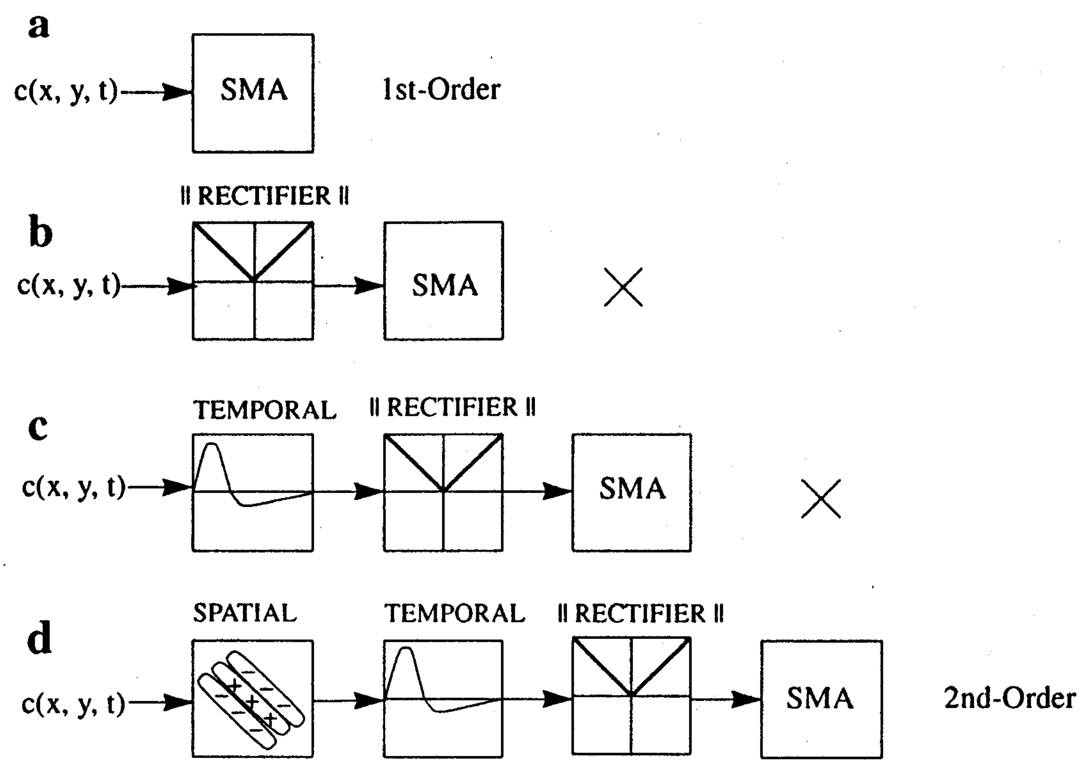
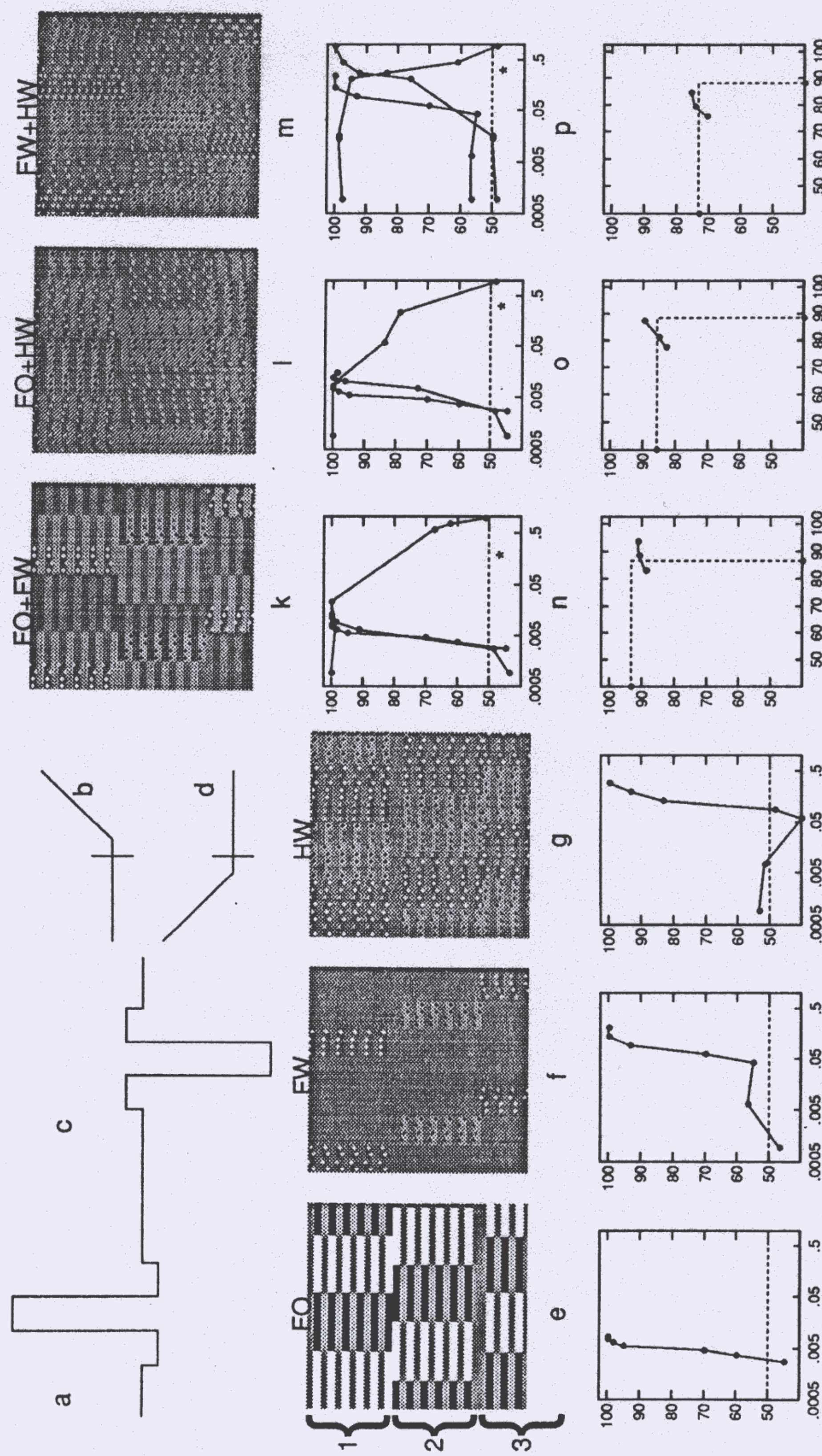


Figure 2. Successive approximations to a model of motion analysis. (a) SMA is Standard Motion Analysis. The input is contrast as a function of space and time c(x,y,t); the output indicates the direction of movement. (b) A rectifier converts 1st-order to 2nd-order analysis and extracts latent 2nd-order motion of stimuli Fig. 1d and 1e but this scheme fails for binary stimuli (Fig. 1f, g, h). (c) Adding a temporal bandpass filter to (b) now enables 2nd-order analysis of stimuli Fig. 1f and 1g but fails for Fig. 1h. (d) Adding a spatial filter creates a "texture grabber" which can extract the latent 2nd-order motion in all the stimuli of Fig. 1.

quilt, and it produces easily visible apparent motion. In Frame 1, areas of high spatial frequency (A_1) alternate with areas of low spatial frequency (B_1). In each successive frame, the entire *ABA-BAB* framework shifts rightward 45 deg, and all the areas A_i and B_i are replaced with new random samples A_{i+1} and B_{i+1} of the same textures. Because they are independent samples, A_i and A_{i+1} are uncorrelated. To create the correlation that is needed to extract motion, there must first be recognition that there are two different textures. This is accomplished by a *texture grabber* — a spatial filter with a different response to the A and B textures plus a rectifier operating on the filter's output. The texture grabber parses the stimulus into areas that have more and less of the grabber's preferred texture, and therefore its output is amenable to standard motion analysis. Chubb & Sperling (1991) proved the necessity of a texture grabber: no pointwise (intensity or purely temporal) transformation is sufficient to expose the 2nd-order motion of texture quilts.

Sufficiency of fullwave rectification. A basic question is whether rectification in 2nd-order processing is fullwave or halfwave. A fullwave rectifier $F(c)$ is a nonnegative, monotonic function of the absolute value of contrast c. A positive halfwave rectifier $F^{+}(c)$ equals $F(c)$ for $c \geq 0$ and otherwise equals 0 (e.g., Fig. 3b). A negative halfwave rectifier $F^{+}(c)$ equals $F(c)$ for $c \leq 0$ and otherwise equals 0 (e.g., Fig. 3d). Stimulus Fig. 1i (Chubb and Sperling, 1989) is a contrast reversing grating, which is a variant of the contrast reversing bar of Fig. 1e. The left-to-right 2nd-order motion of the stimulus of Fig. 1i is completely obvious when seen in central vision, whereas the reverse (1st-order) motion can be seen in peripheral vision. The stimulus of Fig. 1i has the property that the black squares by themselves, or the white squares by themselves, are completely uninformative about the direction of motion or of slant. Thus, simple halfwave rectification would be useless in revealing its motion or slant to directional energy analysis. Nor do reasonable temporal transformations followed by halfwave rectification succeed. But almost every variant of fullwave rectification exposes the motion of Fig. 1i to directional energy analysis. These observations demonstrate that halfwave rectification is not necessary for 2nd-order motion perception. We now consider the question: Is there halfwave motion perception?

Figure 3. Fourier, fullwave and halfwave stimuli and data. (a) Graph of contrast versus space $c(x)$ for a *plus hat.* (b) Output versus input for a positive halfwave rectifier with a nonzero threshold (zero is indicated by the vertical bar). The output is zero for minus hats but positive for plus hats. (c) A *minus hat.* (d) A negative halfwave rectifier (with a threshold). (e) The Fourier stimulus (FO). Three frames of a square-wave grating (even rows) on a uniform background (odd rows). Each frame (1,2,3) shows a portion of the image displayed to the subject. Odd- and even-row stimuli alternate rows in successive frames. (f) Fullwave stimulus (FW). Contrast-reversing hats move left to right. (g) Halfwave stimulus (HW). A row of alternating-contrast hats moves left to right. (h) Psychometric function (percent correct motion-direction judgments versus contrast) for the Fourier stimulus, F0. (i) Psychometric function for FW. (j) Psychometric function for HW. (k,l,m) Compound stimuli: Even and odd rows contain oppositely-directed moving component stimuli as indicated above each panel. (n) Data for one subject viewing FO + FW. The two almost superimposed rising curves (ending in top center) represent psychometric functions for detecting motion-direction of Fourier stimulus as function of Fourier contrast (abscissa) with fullwave masking stimulus set either to zero (left curve) or to the contrast indicated by the asterisk (right curve). The falling curve indicates the contrast threshold for the fullwave grating (with contrast indicated by asterisk) as a function of Fourier masking contrast. (o) Similar to (n) with Fourier component (contrast=abscissa) plus halfwave component (contrast=asterisk) stimuli. (p) Similar to (n) with fullwave component (contrast=abscissa) plus halfwave component (contrast=asterisk) stimuli. (q) Attention operating characteristic (AOC). Ordinate is percent correct Fourier motion judgments; abscissa is percent correct fullwave motion judgments in a particular compound stimulus. Performances (averages of three subjects) in three conditions of selective attention are indicated by points along line. There is small amount of overall improvement by attending to the more difficult component stimulus, but there is absolutely no *selective* improvement for the attended stimulus. Performance in control conditions (attend and report to only one component) is indicated by dashed lines. (r) AOC: Fourier (ordinate) plus halfwave (abscissa). (s) AOC: Fullwave (ordinate) plus halfwave (abscissa).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Fullwave and Halfwave Stimuli

Halfwave hats. Solomon, Sperling, and Chubb's (1993) basic tools for the study of visual halfwave systems are two kinds of halfwave hats, plus hats (Fig. 3a) and minus hats (Fig. 3b). These 2D stimulus elements are called hats because the 3D graph of intensity as a function of space looks like a hat. They are based on the original hat elements of Carlson, Anderson, and Moeller (1980) that were designed to eliminate 1st-order processes. Plus hats have the property that when passed through a positive halfwave rectifier that has a small threshold (Fig. 3b), they produce a large output; when passed through the symmetric negative halfwave rectifier, the output is zero. It is not necessary for the rectifier to have a threshold to produce this selectivity, a soft threshold non-linearity (such as the square law that is usually assumed for near-threshold processing) work almost as well.

Halfwave stimuli. A halfwave stimulus consists of alternating rows of plus and minus hats (Fig. 3g). Whereas plus hats selectively stimulate positive halfwave detectors, and negative hats selectively stimulate negative halfwave detectors, this stimulus would appear as a uniform field to a fullwave detector. In fact, one can go one step further: By varying the amplitude ratio of plus to minus hats, it is possible to find a point of minimum visibility of the halfwave stimulus either for motion or for texture, very much the way one might vary the luminance of green and red stripes to find a point of isoluminance. For motion, there is a sharp minimum, different for every observer. The average ratio is 1.17 indicating that, on the average, minus hats are somewhat more effective at stimulating the fullwave system than plus hats, but that they can be perfectly balanced. Once the hats are fullwave balanced, the halfwave stimulus should appear completely uniform to the fullwave system. Of course, the luminances of the hats are physically balanced for invisibility to the 1st-order (Fourier) analysis at the frequencies of the to-be-detected stripes, so the halfwave stimulus also is neutral to the 1st-order system.

Every observer easily sees the stripes in a static halfwave stimulus, indicating that there is a halfwave texture system. Indeed, halfwave theories of spatial vision have been proposed by several of the participants in this conference (Graham, Malik, Morgan, Watt). But only 1/3 of Solomon & Sperling's (1994) observers were able to detect the direction of motion of halfwave stimuli. In few instances, giving deficient subjects extensive practice did not seem to improve their halfwave performance. This suggests that for those who do not already possess it, the ability to detect halfwave motion is not easily acquired. The psychometric function (percent correct as a function of halfwave contrast) for a subject who has excellent ability to discriminate halfwave motion is shown in Fig. 3j.

Fullwave stimulus. The fullwave analog to the stimulus of Fig. 1i is shown in Fig. 3f; it becomes ambiguous after halfwave rectification. Because it is composed of hats, it is also invisible to 1st-order directional energy analysis at the frequencies of the stripes. Contrast threshold for direction discrimination of the fullwave stimulus is about 0.05 (Fig. 3i), almost an order-of-magnitude less than the contrast threshold for the halfwave stimulus.

Fourier stimulus. The Fourier stimulus is a squarewave grating of the same spatial frequency as the others. Squarewave contrast threshold for direction discrimination is about 0.005, an order-of-magnitude less than for the fullwave stimulus.

Relative efficiency computation. However, most of the sensitivity difference between the Fourier (1st-order) stimulus and the 2nd-order stimuli rests in the stimuli themselves. If we assume a square-law contrast rectifier (i.e, a power computation), we find that there is much more stimulus energy in the Fourier stimulus than the others. Relative to the Fourier stimulus, at threshold, the fullwave and halfwave stimuli, respectively, require 1.9 and 33.2 more contrast power, yielding a fullwave relative power-efficiency of .52% and a halfwave efficiency of .030 %. However, if an absolute value rectifier is assumed then, for all subjects, the efficiency of discriminating fullwave stimuli is actually greater than that of Fourier stimuli (Solomon & Sperling, 1994).

Once the stimulus contrast power is taken into account, 2nd-order fullwave motion discrimination is almost as or perhaps more efficient than 1st-order. But, halfwave motion discrimination lags behind by more than a factor of 10, even for the subset of the population especially chosen for their ability to make this discrimination. The conclusions are that 2nd-order fullwave computation ranks with 1st-order Fourier motion as a major computation that has been sufficiently important to evolution to have evolved high efficiency. Halfwave motion perception, even for the few who possess it, is a relatively weak process.

In the kinetic depth effect (KDE), Dosher, Landy, and Sperling (1989) showed it was the 2D *motion flowfield* that gave rise to a 3D perceptual structure. However, only 1st-order motion flowfields transmit the level of resolution required to make 3D shape discriminations (Sperling, Landy, Dosher, and Perkins, 1989). Although direction discrimination of fullwave motion is an efficient process, the fullwave motion computation is too coarse to be useful in KDE.

Concurrent Motion-Discrimination Tasks

Between-systems transparency. Superimposing two sinewave motion signals of the same spatial and temporal frequency traveling in opposite directions produces a "counterphase flickering" grating in which no motion is perceived. When the spatial frequencies differ sufficiently (e.g., by more than an octave), superposition fails to produce cancellation of apparent motion--instead, motion transparency is perceived. When 1st- and 2nd-order systems are involved, the situation is similar to the case of different spatial frequencies: oppositely-directed equal-strength stimuli produce transparency, not cancellation.

Solomon and Sperling (1994) systematically studied interactions between superimposed, independently moving, 1st- and 2nd-order stimuli. A fullwave motion stimulus of contrast 0.16 was presented together with a Fourier square wave that varied in contrast from from 0 .001 to 0.93 on successive trials. The subject was asked the direction of either the 1st-order stimulus or the 2nd-order stimulus. The two rising curves in Fig. 3n represent the accuracy of 1st-order motion-direction judgments as a function of Fourier contrast, with and without the fullwave masking stimulus. The falling curve represents the accuracy of motion-direction judgments of the the 2nd-order stimulus.

Two important facts are apparent in the data of Fig. 3n: (1) There is a significant range of contrasts where the subject can correctly report the direction of either stimulus (i.e., there is motion transparency). (2) There is relatively little cross masking (the two rising curves nearly overlap). The low level of cross masking is important because it rules out the possibility of detecting 2nd-order motion by spillover into the 1st-order domain or vice versa--any spillover components would be rendered useless by the large, already present "other" stimulus. Similarly, the motion transparency also indicates that there must be separate computational systems.

Figure 3o shows results when a fixed-contrast halfwave stimulus is masked by Fourier squarewaves of various contrasts. The data are similar to 3n and again, the conclusion is that halfwave and Fourier stimuli are analyzed in largely independent channels.

Figure 3p shows that, when a constant halfwave stimulus is masked by various fullwave stimuli, there is no significant region in which both stimuli can be judged independently. The subjects' problem is evident in the subset of stimuli in which fullwave and halfwave stimuli travel in opposite directions. The appearance is one of motion transparency, but subjects are unable to link the directions of motion with the appropriate fullwave and halfwave components.

Attention Operating Characteristics, AOCs. Solomon and Sperling (1994) selected a pair of approximately equal-strength, maximally visible components from each of the three pairs of superimposed stimuli (Fourier/Fullwave, Fourer/Halfwave, Fullwave/Halfwave). The choices were appropriate for each subject. As before, the subjects were presented stimuli composed of two components moving in randomly and independently chosen directions. Now, subjects were required to report both directions—in effect, to perform two concurrent tasks. In various conditions, they were instructed to give primary attention either to one component, to the other, or to divide attention equally between both. In control conditions, subjects judged only one or only the other component.

Task independence and resources in AOCs. The data from concurrent tasks are the joint performances on the two tasks (in this case, accuracy of motion-direction judgments) as a function of the attentional condition. These dual response data trace out an AOC shown in Figs. 3q,r,s. The ordinate represents accuracy of motion-direction judgments of one motion component (the Fourier component in Figs. 3q, r, the fullwave component in Fig. 3s); the abscissa represents judgments of the other motion component. If the data were to lie on a diagonal line connecting the two control conditions (Figs. 3q,r,s), it would indicate total dependence on the same processing resource. However, the data for the three stimulus pairs all lie near the independence point, the point at the intersection of perpendiculars to the axes drawn through the control data points (dotted lines). This indicates that totally separate resources are involved (Sperling & Dosher, 1986), in this case, independent motion computations. The conclusion is that Solomon and Sperling's (1994) subjects could perform two independent motion computations. The limiting resource could not be consciously controlled; that is, at least one of the motion computations in each pair of stimuli was automatic and did not require attentional resources.

The fullwave and halfwave stimuli obviously did involve a capacity limit because subjects were unable to judge both motions in equal-strength stimuli. However, giving full attention to one or the other motion component, or attending equal both, all produced equal levels of performance. This means that allocation of the limiting resource in this process was not under conscious control.

Spatial Interactions

Contrast-contrast. In a well known brightness illusion, a patch of gray looks brighter when it is surrounded by black (Fig. 4a) than when surrounded by white (Fig. 4b). This is a 1st-order illusion. The 2nd-order analog (Chubb, Sperling, and Solomon, 1989) is a contrast-contrast illusion in which a patch of random texture surrounded by a high contrast texture (Fig. 4d) looks less contrasty than a similar patch surrounded by "texture" of zero contrast (Fig. 4c). Although this 2nd-order illusion works in a static illustration, it is even stronger in dynamic displays, e.g., when new random samples of the textures appear every 1/8th sec. The contrast-contrast illusion is specific to spatial frequency. When the spatial frequency of the center and the surround differ by an octave (Figs. 4e and 4g) contrast-contrast inhibition is much less than when the spatial frequencies are the same (Fig. 4f). Orientation also matters at frequencies greater than about 3 cycles/degree so that parallel gratings in the center and surround produce greater contrast-contrast then do perpendicular

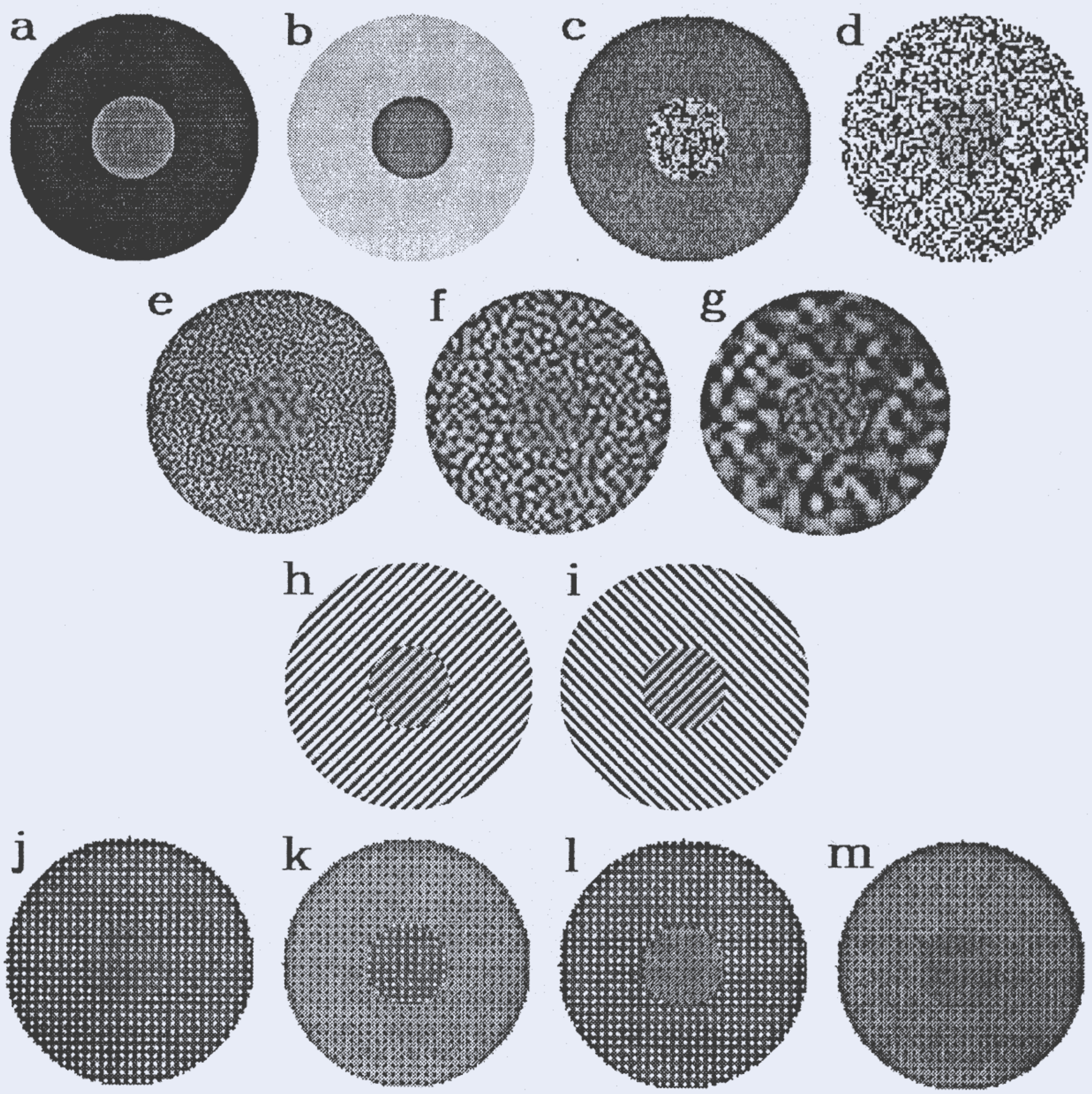

Figure 4. Spatial interactions. (a,b) Luminance contrast. The central disk has the same contrast in (a) and (b). (c,d) Contrast-contrast. The texture in the central disk has the same contrast in (a) and (b). (e,f,g) The texture in the central disk has the same contrast in each of (e,f,g) and so does the surrounding annulus but, relative to (f), the annular spatial frequency is an octave higher in (e) and and octave lower in (g). (h,i) The effect of the orientation of the grating in the annular surround on the perceived contrast of the grating in the central disk. (j-m) The effect of plus versus minus hats in producing spatial interactions. Center/surround: (j) +/+, (k) +/-, (l) -/+, (m) -/-.

gratings (Figs. 4h and 4i). (Solomon, Sperling, and Chubb, 1993; Cannon & Fullencamp, 1991).

When the contrast textures are produced by hats rather than by gratings or visual noise, the magnitude of the illusion is completely indifferent to the signs of the hats in the center and the surrounds (Solomon, Sperling, and Chubb, 1993). Plus hat surrounds produce just as much contrast inhibition on minus hat centers as do minus hat surrounds, and vice versa (Figs. 4j,k,l,m). That the signs of the inhibiting and inhibited hats are irrelevant means that lateral contrast inhibition is a fullwave process.

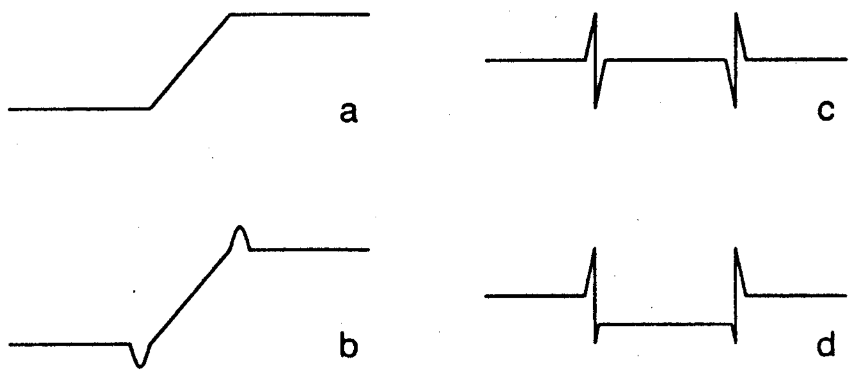

Figure 5. (a) Spatial luminance ramp for 1st-order Mach band or spatial contrast ramp for 2nd-order Mach band. (b) Perceived brightness (or contrast) as a function of luminance (1st-order) or perceived texture contrast (2nd-order) of stimulus (a). (c) Spatial pattern for the Craik-O'Brien-Cornsweet illusion. (d) The illusion: The perceived brightness (or contrast) of pattern (c).

2nd-order Mach bands. Mach bands are illusory brightness enhancements and darkness enhancements (Fig. 5b) at the points where an intensity ramp joins a uniform brightness plateau (Fig. 5a). Mach bands usually are taken to be indicative of the same lateral inhibitory interactions that produced the lightness (Fig. 4a,b) and the contrast-contrast illusions (Fig. 4c,d). Lu and Sperling (1993) replaced the 1st-order luminance stimulus (Fig. 5a) with 2nd-order contrast modulation to produce a 2nd-order ramp (contrast modulation of a random noise carrier). Psychometric measurements showed that the induced 2nd-order (contrast) Mach bands were equal in magnitude the 1st-order bands induced by a luminance ramp.

In the Craik-O'Brien-Cornsweet illusion, the mean brightness of a disk surrounded by two thin rings having higher and lower brightness, respectively, (Fig. 5c) causes the interior patch to appear to have overall lower brightness (Fig. 5d). Again, Lu and Sperling (1993) found the corresponding 2nd-order Craik-O'Brien-Cornsweet illusion to be approximately equal in magnitude to the 1st-order illusion.

Both the 2nd-order Mach bands and the 2nd-order Craik-O'Brien-Cornsweet illusions can be produced with textures composed of random textures composed of hats as well as of random noise. For hat-stimuli, the illusions are indifferent to the signs of the hats. Halfwave versions of the stimuli in which the illusion depended on the sign (instead of on the amplitude) of the hats caused the illusions to fail completely. This shows, not surprisingly, like the lateral contrast-contrast inhibition (Fig. 3), the lateral interactions responsible for 2nd-order Mach bands and the Craik-O'Brien-Cornsweet illusions are entirely fullwave interactions.

Conclusion

2nd-order processes are ubiquitous in perception and, after a strong initial nonlinearity (fullwave rectification), seem to follow the same principles as 1st-order interactions.

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