



Full-Wave and Half-Wave Rectification in Second-Order Motion Perception

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Microbalanced stimuli are dynamic displays which do not stimulate motion mechanisms that apply *standard* (Fourier-energy or autocorrelational) *motion analysis* directly to the visual signal. In order to extract motion information from microbalanced stimuli, Chubb and Sperling [(1988) *Journal of the Optical Society of America*, 5, 1986–2006] proposed that the human visual system performs a rectifying transformation on the visual signal prior to standard motion analysis. The current research employs two novel types of microbalanced stimuli: *half-wave stimuli* preserve motion information following half-wave rectification (with a threshold) but lose motion information following full-wave rectification; *full-wave stimuli* preserve motion information following full-wave rectification but lose motion information following half-wave rectification. Additionally, *Fourier stimuli*, ordinary square-wave gratings, were used to stimulate standard motion mechanisms. Psychometric functions (direction discrimination vs stimulus contrast) were obtained for each type of stimulus when presented alone, and when masked by each of the other stimuli (presented as moving masks and also as nonmoving, counterphase-flickering masks). Results: given sufficient contrast, all three types of stimulus convey motion. However, only one-third of the population can perceive the motion of the half-wave stimulus. Observers are able to process the motion information contained in the Fourier stimulus slightly more efficiently than the information in the full-wave stimulus but are much less efficient in processing half-wave motion information. Moving masks are more effective than counterphase masks at hampering direction discrimination, indicating that some of the masking effect is interference between motion mechanisms, and some occurs at earlier stages. When either full-wave and Fourier or half-wave and Fourier gratings are presented simultaneously, there is a wide range of relative contrasts within which the motion directions of both gratings are easily determinable. Conversely, when half-wave and full-wave gratings are combined, the direction of only one of these gratings can be determined with high accuracy. Conclusions: the results indicate that three motion computations are carried out, any two in parallel: one standard (“first order”) and two non-Fourier (“second-order”) computations that employ full-wave and half-wave rectification.

Motion Non-Fourier motion Rectification Transparency Attention

INTRODUCTION

In order to determine the direction of motion of most objects, it suffices to perform a spatiotemporal correlation of intensity in the visual field. This is *standard motion analysis*. Equivalently, the same motion is revealed by a Fourier analysis of the raw spatiotemporal luminance function (Chubb & Sperling, 1991). Many researchers have shown however, that humans are able to determine the direction of motion of types of stimuli for which standard motion analysis alone is non-informative (Ramachandran, Ginsburgh & Anstis, 1973; Sperling, 1976; Petersik, Hicks & Pantle, 1978; Ramachandran *et al.*, 1983;

Lelkins & Konderink, 1984; Derrington & Badcock, 1985; Green, 1986; Pantle & Turano, 1986; Bowne, McKee & Glaser, 1989; Cavanagh, Arguin & von Grunau, 1989; Turano & Pantle, 1989). Chubb and Sperling (1988) proposed that the process by which motion information is extracted from these “drift-balanced” stimuli consists of a spatiotemporal linear filter, followed by a rectifying nonlinearity, followed by standard motion analysis.

Definitions

In this paper, we evaluate two candidate schemes of rectification: full-wave and half-wave. A few formal definitions will facilitate the subsequent discussion.

Stimuli. Our stimuli are described by a non-negative, discrete, luminance $I(x, y, t)$ which is a function of space x, y and time t .

Mean luminance. Every frame of each of our stimuli has the same average luminance I_0 .

Pixel contrast, $c(x, y, t)$. The term *pixel contrast* refers

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to the deviation of a particular stimulus point from mean luminance $c(x, y, t) = [l(x, y, t) - l_0]/l_0$.

Full-wave rectification. Full-wave rectification means any monotonically increasing function of the *absolute value* of pixel contrast.

Half-wave rectification. Positive half-wave rectification means any monotonically increasing function of pixel contrast, that is zero for pixel contrasts equal to or less than zero. Negative half-wave rectification means any monotonically decreasing function of pixel contrast, that is zero for pixel contrasts equal to or greater than zero.

Theory

Chubb and Sperling (1989) demonstrated that a sideways stepping, contrast-reversing grating (see Fig. 1) appears to change direction when viewed at different distances. They cite this phenomenon as evidence of two separate mechanisms; a *first-order* mechanism which applies standard motion analysis to the image, and a *second-order* mechanism which applies standard motion analysis following full-wave rectification of the image. This stimulus is special because its motion direction is ambiguous to any system receiving a half-wave rectified

version of the raw stimulus. One purpose of the present research is to determine whether or not humans can detect motion that is ambiguous both to first-order motion analysis and to second-order motion analysis involving full-wave rectification.

Half-wave systems encode contrast. When it is not necessary to transmit information about average luminance, visual information is efficiently coded by tandem positive and negative half-wave systems. Stimulus points having positive pixel contrasts activate only the positive half-wave system, and stimulus points having negative pixel contrasts activate only the negative half-wave system. In such a scheme, individual mechanisms are silent except to record deviations from average luminance. Tandem half-wave systems have been proposed previously (Watt & Morgan, 1985). Direction discrimination is one task in which it is not necessary to transmit average luminance. Therefore, we suppose that, prior to motion extraction in the visual system, stimuli undergo transformations similar to positive and negative half-wave rectification.

On-center cells selectively encode increments; off-center cells selectively encode decrements. While both on-center and off-center ganglion and LGN cells maintain a steady

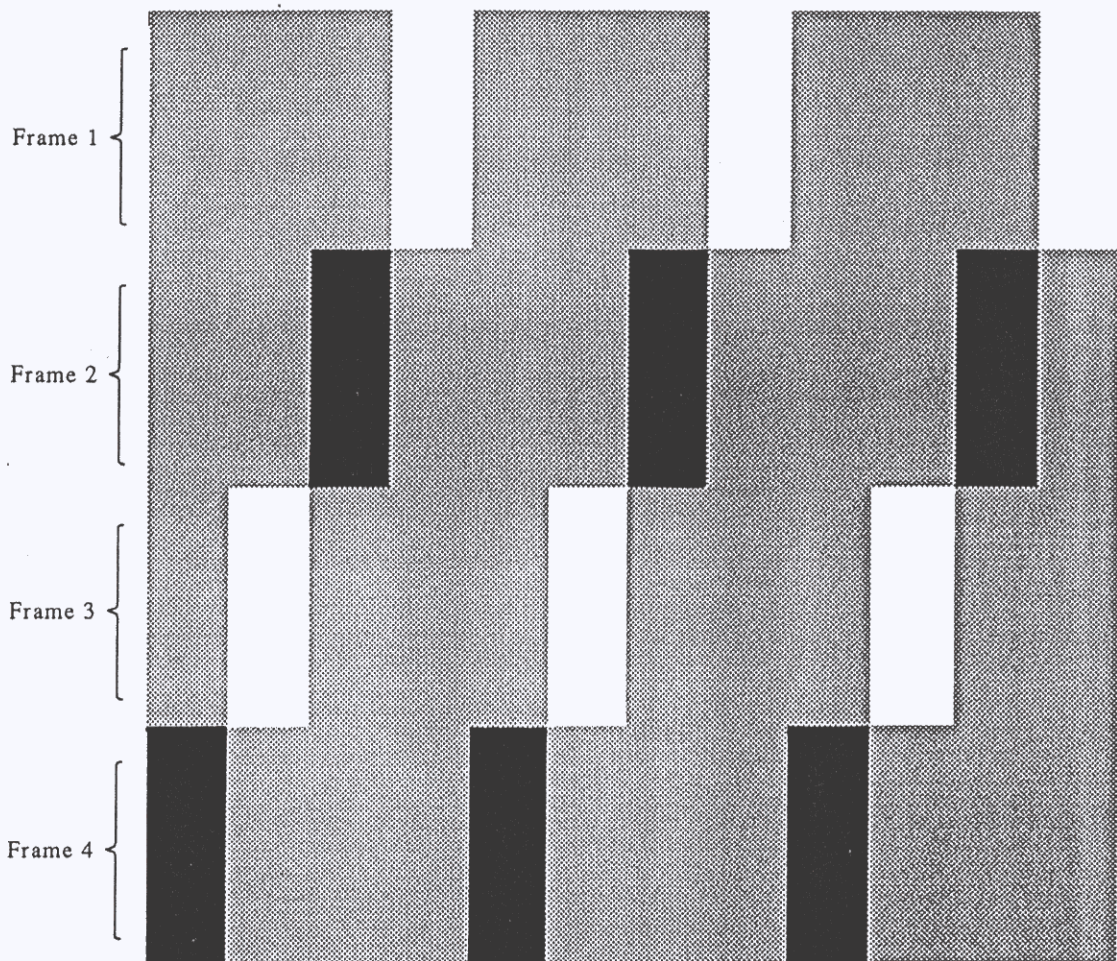


FIGURE 1. Schematic cross-section of Chubb and Sperling's (1989) stimulus Γ , a repeating four frame stimulus that conveys rightward first-order (Fourier) motion when viewed from near in central vision and leftward second-order (non-Fourier) motion when viewed peripherally or from afar. Each frame, 1, 2, 3 and 4 is repeated four times at 60 Hz; the entire stimulus repeats every 4/15 sec.

base rate of firing, it seems unlikely that contrast information from suprathreshold stimuli can be adequately signaled by *decreases* in the base firing rates. In the extreme, no cell can distinguish between two stimuli, each of which has sufficient contrast to cause a complete cessation in firing. Less extreme stimuli may slow the firing rate down enough so that the rate itself may only become discernible to subsequent processing stages after some considerable time (Enroth-Cugell & Robson, 1984). However, stimuli of contrast which cause a decrease in the firing rate of on-center cells should simultaneously cause an increase in the firing rate of off-center cells, and vice versa. Thus, contrast information can be adequately coded by an increase in the firing rate of one of the two systems.

Indeed, selective, pharmacological blocking of on-center cells in monkeys has been demonstrated (Schiller, Sandell & Maunsell, 1986) to severely impair detection of bright spots, without affecting dark spot detection. This finding supports the notion that local luminance increments are coded by the on-center system, and local luminance decrements are coded by the off-center system.

Stimuli that selectively stimulate half-wave, full-wave and Fourier systems

Our half-wave and full-wave stimuli (see below), are composed of textures designed to investigate mechanisms which receive input from either on-center or off-center neurons, but not both. [See Solomon, Sperling and Chubb (1993), for a more thorough discussion of these textures.] In theory, the bright spots in our textures will selectively increase the firing rates of on-center cells in whose receptive field centers they fall, and the dark spots will increase the firing rates of off-center cells in whose receptive field centers they fall. The true physiological selectivity of these textures has no bearing on our measurements or conclusions. We simply wish to explain our motivation for constructing these particular stimuli.

Half-wave stimuli. Figure 2(hw) depicts four frames of a rightward moving stimulus whose direction is ambiguous to both first-order motion analysis and to any analysis involving full-wave rectification. Chubb and Sperling (1988) have demonstrated that purely linear transformations of drift-balanced stimuli, such as this, are ineffective in revealing directional information to standard motion extraction mechanisms. Full-wave rectification of this stimulus eliminates systematic differences between frames, and consequently removes all directional information.

Alternatively, half-wave rectification of this stimulus can reveal its direction of motion to standard mechanisms. This rectification can be accomplished by an array of operators that signal local increases or decreases in pixel contrast with a sigmoidal response relationship similar to that observed in LGN and cortical neurons. Following such a half-wave transformation, either the energy from stimulus regions containing black dots or the energy from stimulus regions containing white dots is greatly attenuated, and the rightward motion of such

a half-wave stimulus is revealed to standard mechanisms.

Full-wave stimuli. A drift-balanced, full-wave stimulus whose direction is revealed by full-wave rectification is shown in Fig. 2(fw). Half-wave rectification with a threshold (i.e. rectification that is zero for small values of pixel contrast) would remove all directional information from this full-wave stimulus. For example, positive half-wave rectification that produces a positive output for white dots and a zero output for the slightly above average backgrounds of black dots would produce a zero output for every other frame of the stimulus. The energy-containing regions of the remaining frames are situated 180 deg out of phase, and therefore do not indicate a direction of motion. Full-wave rectification of this stimulus produces equal output for regions containing black dots and for regions containing white dots, and thereby can provide directional information to standard mechanisms.

Half-wave rectification alone cannot reveal the directional information of full-wave stimuli to standard mechanisms. However, half-wave rectification preceded by temporal differentiation can. For example, consider a temporal filter that produces a positive, transient response to both the offset of the black hats and the onset of the white hats. Such a filter, when followed by a positive half-wave rectifier, yields veridical directional information to standard mechanisms. We will demonstrate that any such "half-wave contamination" of our full-wave stimuli will be inconsequential with respect to our measurements and conclusions.

Fourier stimuli (square-waves). Figure 2(f) illustrates a square-wave Fourier stimulus that stimulates first-order motion mechanisms. The extent to which Fourier stimuli incidentally stimulate half-wave and full-wave systems will be considered below.

Addition of two stimuli

Our stimuli have been constructed so that each uses only half the available pixels. This permits any two to be added in a way that preserves the pixel contrasts of each component.

Consider the simultaneous presentation leftward and rightward moving square-wave gratings. The two components of the resulting composite stimulus do not appear to move transparently; rather the display appears to flash in counterphase fashion. The same result holds for combinations of leftward and rightward moving full-wave stimuli and leftward and rightward moving half-wave stimuli. This indicates that both the leftward and rightward moving components of each composite stimulus excite the same pathways in the visual system. When their contrasts are equated, the motions of the two components cancel each other.

The construction of our stimuli also allows for the simultaneous presentation of two different types of component. Thus, for example, we can present a leftward moving Fourier component and a rightward moving full-wave component, at the same retinal location, simultaneously. When the observer is capable of

accurately determining the directions of both of these components, we conclude that each grating stimulates a different motion system.

Parallel visual mechanisms. Parallel visual mechanisms exist at many different spatial scales. When two stimuli of the same type (e.g. Fourier) but of different spatial frequencies appear to move transparently, we conclude each is stimulating a different scale within a motion system. However, the motion signal carried by each of our stimuli has the same wavelength and speed. When two different types of stimuli (with the same spatial and temporal frequency) appear to move transparently in opposite directions, we conclude that each is stimulating a different *type* of motion system, not a different *scale* within the same motion system.

Masking. When two moving stimuli are combined at the same spatial location, invariably some amount of masking occurs. By comparing performance decrements with moving and non-moving (counterphase) masks, we are able to determine the extent to which interference occurs prior to motion extraction within the visual system.

Pretest for half-wave sensitivity. In a pilot experiment, 18 naive subjects were shown 80 displays of half-wave stimuli, and asked to judge the direction of motion of each display. Each display consisted of one full temporal cycle at 4 Hz. Feedback was given after each presentation. Of these subjects, six got more than 45 of their last 50 judgments correct (>90%). This result suggests that some people may have second-order motion mechanisms that utilize half-wave rectification. Four of these six subjects were used in the main experiment. Of the remaining 12 subjects, five scored 70–88% and seven got less than 70% correct, where 50% is chance. One subject, who initially scored 64% correct, received 100 training trials each day for 2 weeks. He was unable to learn the task. This suggests that the ability to use half-wave transformations to resolve motion direction stimuli is not easily learned and perhaps may not be learnable—subjects either have it or they do not.

Overview

Four psychophysical experiments were run to investigate the possibility that second-order motion perception mechanisms might use half-wave rectification. In Expt 1, for each subject, we manipulate the ratio of positive pixel

contrast to negative pixel contrast, to find the half-wave stimulus that minimizes full-wave contribution to direction discrimination. That is, we determine the pure half-wave stimulus for that subject. Experiment 2 demonstrates that these half-wave stimuli do indeed convey directional information. Observers process information (contrast energy) contained in a half-wave stimulus much less efficiently than they process information contained in a full-wave stimulus, which is processed even less efficiently than a Fourier stimulus. Psychometric functions obtained in Expt 2 further show that both half-wave and full-wave direction discrimination is resistant to a high degree of masking by (Fourier) square-wave gratings. Psychometric functions obtained in Expt 3 indicate that moving masks are only slightly more effective than counterphase masks at hampering direction discrimination. This is also true when the target component is half-wave and the mask component is full-wave. Attention operating characteristics obtained in Expt 4 show that subjects are able to determine the directions of any two types of stimulus simultaneously, without any loss of accuracy.

GENERAL METHODS

Subjects

One of the authors (JS) and four of the six best (out of a total of 18) observers from the pilot experiment served in Expts 1 and 2. Three of these subjects served in Expts 3 and 4.

Apparatus

The experiments used an ATVista image display system to present displays on a Leading Technologies 1230V (12 in. diagonal white) monochrome graphics monitor, with a mean luminance of 44.1 cd/m². The screen was viewed binocularly at distance of 0.3 m and subtended 17 × 17 deg of visual angle.

Stimuli

The atomic component of all the drift-balanced stimuli used in these experiments is a 3 × 3 pixel array called a *hat*. In a random texture made of white hats, every third pixel of every column (the center of the hat) has a positive pixel contrast. Similarly, in a random texture made of black hats, every third pixel of every column has

FIGURE 2 (*facing page*). Cross-sections of stimuli in the current experiments. (*hw*) Half-wave stimulus. This stimulus consists of four frames, each composed of alternating regions of randomly placed black and white hats. It conveys rightward second-order motion. Its motion is revealed by half-wave rectification followed by standard motion analysis. For this stimulus, standard motion analysis is uninformative following linear transformations or full-wave rectification (*fw*) This full-wave stimulus is composed of $\frac{1}{2}$ cycle-wide regions of randomly placed hats. Odd numbered frames contain only white hats, even frames only black hats. Full-wave rectification followed by standard motion analysis reveals its rightward motion. Linear transformations or half-wave rectification followed by standard motion analysis are uninformative. (*f*) Cross-section of the Fourier stimulus, a rightward-stepping square-wave grating. Its motion is readily extracted by standard motion analysis (first-order motion mechanisms). (*hw + f*) Cross-section of a half-wave + Fourier composite stimulus. Spatially disjoint half-wave and Fourier gratings are added. The half-wave component moves to the right, the Fourier component to the left. (*fw + f*) Cross-section of a full-wave + Fourier composite stimulus. The full-wave component moves to the right, the Fourier component to the left. (*hw + fw*) Cross-section of a half-wave + full-wave composite stimulus. The half-wave component moves to the right, the full-wave component to the left.

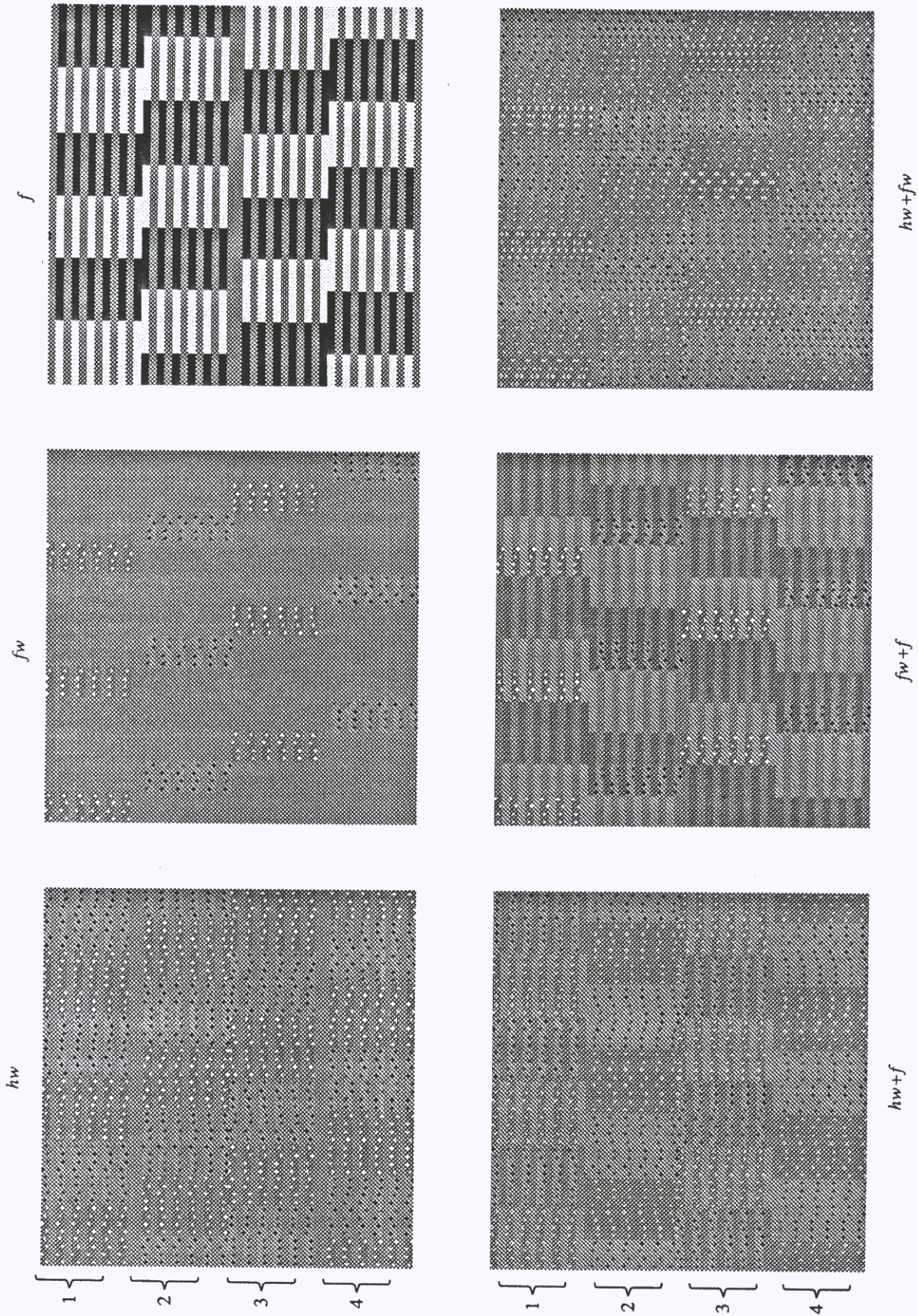


FIGURE 2. Caption opposite.

a negative pixel contrast. The intensities of the other pixels are chosen so that the mean luminances of the textures made of black and white hats are equal. Finally, the entire texture is magnified by a factor of 2, and each hat becomes a 6×6 pixel array. The bright or dark "hat centers" become two pixels wide by two pixels long. When viewed from sufficiently far, so that individual hats cannot be resolved, all textures made of hats appear to be uniform fields indistinguishable from the background. At the experimental viewing distance of 0.3 m, an individual hat subtended 0.31 deg of visual angle and the entire motion stimulus (consisting of 3 full cycles) subtended 15×15 deg of visual angle.

Three types of stimulus were used in these experiments: "Fourier", "half-wave" and "full-wave" (Fig. 2). The Fourier stimuli were square-wave gratings. The half-wave stimuli were square waves in which each half cycle was a random texture of either black or white hats. The full-wave stimuli were one-quarter-cycle wide rows of either black or white hats (polarity flipped every frameblock). All stimuli shifted laterally 90 deg

every frameblock. (A *frameblock* is a consecutive series of identical frame refreshes; typically 4 refreshes at a rate of 60 refreshes per sec.) Any two of the three types of stimulus can be combined by interleaving one-hat wide horizontal rows of each. For these composite stimuli, each strip alternates between each component each frameblock (Fig. 3). Row alternation prevents the subject from ignoring the irrelevant component by simply attending to one row.

Stimulus contrast

The luminance function that describes our Fourier stimulus assumes only three values; that of the bright pixels, that of the dark pixels and mean luminance. The luminance functions that describe our drift-balanced stimuli assume only five values each, that of the white hat centers, that of the white hat surrounds, that of the black hat centers, that of the black hat surrounds and mean luminance. We define the *contrast* of any stimulus as a single number—the peak pixel contrast of that stimulus.

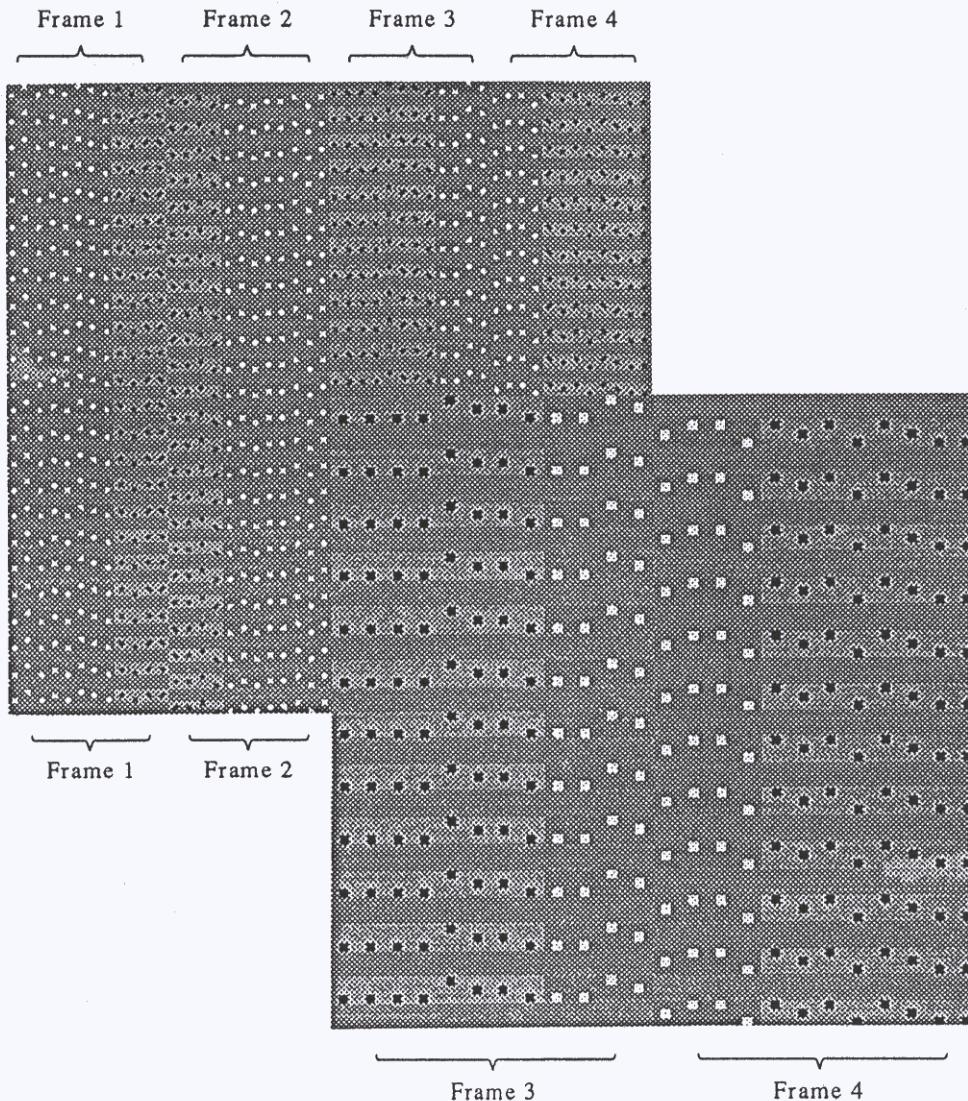


FIGURE 3. Detailed cross-section of a half-wave stimulus. In this representation, spatially adjacent portions of frames 3 and 4 have been enlarged and placed horizontally adjacent to illustrate that motion information is carried by different rows on successive frames.

Luminance calibration

A hardware modification of a standard, 256-level, black and white display allowed us to obtain 4096 distinct gray levels. The dials on the monitor were set to maximum brightness and medium contrast (a preset notch in the dial). With this setting, the luminance of the monitor was 2.9 cd/m² when every pixel was given the lowest gray level and 85.3 cd/m² when every pixel was given the greatest gray level. We chose the mean luminance to be that value which, when it is assumed by every pixel, produces $\frac{1}{2}(85.3 + 2.9) = 44.1$ cd/m². The maximum obtainable pixel contrast for any stimulus point is thus $(85.3 - 44.1)/44.1 = 0.934$. At any one time, only 256 gray levels can be stored in the ATVista's memory. Thus two separate "lookup tables" were constructed, one which covered the entire range of obtainable gray levels, and one which covered one-eighth this range. This latter lookup table was linearly interpolated from the former. These lookup tables were constructed so that for every "hat center" pixel contrast there is a corresponding "hat surround" pixel contrast that is oppositely signed and has one-eighth the magnitude. Textures made of hats, so determined, appear to be uniform fields at mean luminance, when viewed from afar. In this way, the hats automatically compensate for any CRT deficiencies.*

General procedure

For each experiment, the subject sat in a dark room and viewed the display binocularly. The only source of illumination was the light from the continuously illuminated display. The subject was instructed to initiate each trial with a key press, after fixating on a cue spot. Immediately after the key press, one of the six stimuli was presented (half-wave, full-wave, Fourier, half-wave + Fourier, full-wave + Fourier or half-wave + full-wave). The display consisted of five frameblocks of four refreshes each (at a rate of 60 refreshes per sec). The total display duration of $20/60 = 0.33$ sec insures that subjects cannot track a stimulus with eye movements. The first frameblock and the last frameblock were identical. Starting phases and directions of motion were randomized. For trial blocks in which composite stimuli were displayed, the number of trials in which the two components moved in the same direction was equal to the number of trials where the two components moved in different directions. The pattern of hats was randomized for each frameblock (and it remained constant within

each frameblock). The subject reported direction of motion with a key press. Tonal feedback indicated the actual direction of motion.

EXPERIMENT 1

While the luminance calibration is effective in removing Fourier contamination from the drift-balanced stimuli, Expt 1 is required to remove full-wave contamination from the half-wave stimuli. Suppose that the visual system were to utilize an *imperfectly symmetric* full-wave rectifying mechanism. Such an asymmetric transformation of our half-wave stimulus could indeed preserve full-wave directional information. Experiment 1 is a psychophysical calibration procedure designed to find the ratio of positive hat contrast to negative hat contrast that minimizes the subject's ability to discriminate between opposite directions of motion, i.e. the contrast ratio that exactly balances the contribution of positive and negative hats to the full-wave mechanism.

Procedure

In Expt 1, it was necessary to use moderate stimulus contrasts for some subjects, because high stimulus contrasts resulted in perfect performance. In order to get an approximate estimate of threshold for half-wave stimuli (with possible full-wave contamination), we employed a staircase procedure (see Procedure, Expt 2). This procedure estimated the stimulus contrast which yields a 71% correct direction discrimination rate for a half-wave stimulus whose black and white hat centers have pixel contrasts of equal physical magnitude, but opposite sign.

The method of constant stimuli was used to determine the ratio of black-hat-center pixel contrast/white-hat-center pixel contrast, that yielded the poorest half-wave direction discrimination performance. Initially, seven ratios were used, 60 trials per ratio. For the "baseline" stimulus, the contrasts of black-hat-center pixel and the white-hat-center pixel contrast were equal. That is, the black/white contrast ratio was -1 . The magnitude of the pixel contrast of each hat center was either 0.110 or that corresponding to the best estimate for 71% correct, whichever was smaller. Three other stimuli had white hats with lower contrast; the rest had black hats of lower contrast.

The method of constant stimuli procedure was repeated twice, over a narrower range of ratios, using the ratio that yielded the poorest performance in the previous procedure as the new baseline. In each of these iterations, the overall stimulus contrast was boosted so that performance did not bottom out. Specifically, the maximum pixel contrast magnitude was set to 0.110.

Results

Figure 4 shows the results for subject PS, from the last iteration of the method of constant stimuli procedure. This is the narrowest range of black-hat-center pixel contrast/white-hat-center pixel contrast ratios over which the data assumed a "V" shape. For PS, the

*For the coarser lookup table, mean luminance was assigned to value #128. Maximum luminance was assigned to value #248 and minimum luminance was assigned to value #8. A texture of "hats" was then displayed on a mean-luminant background. The hat centers were given value #248. The intensity of the hat surrounds was then varied until the entire texture disappeared. This intensity was assigned to value #113. The values #114-#127 were then interpolated. Subsequently, for hat surrounds with values $\#(128-n, n = 1, 2, \dots, 15)$, values $\#(128 + 8n)$ were then determined by finding those intensities which, when given to the hat centers, made the entire texture disappear. The lower half of the lookup table was similarly determined.

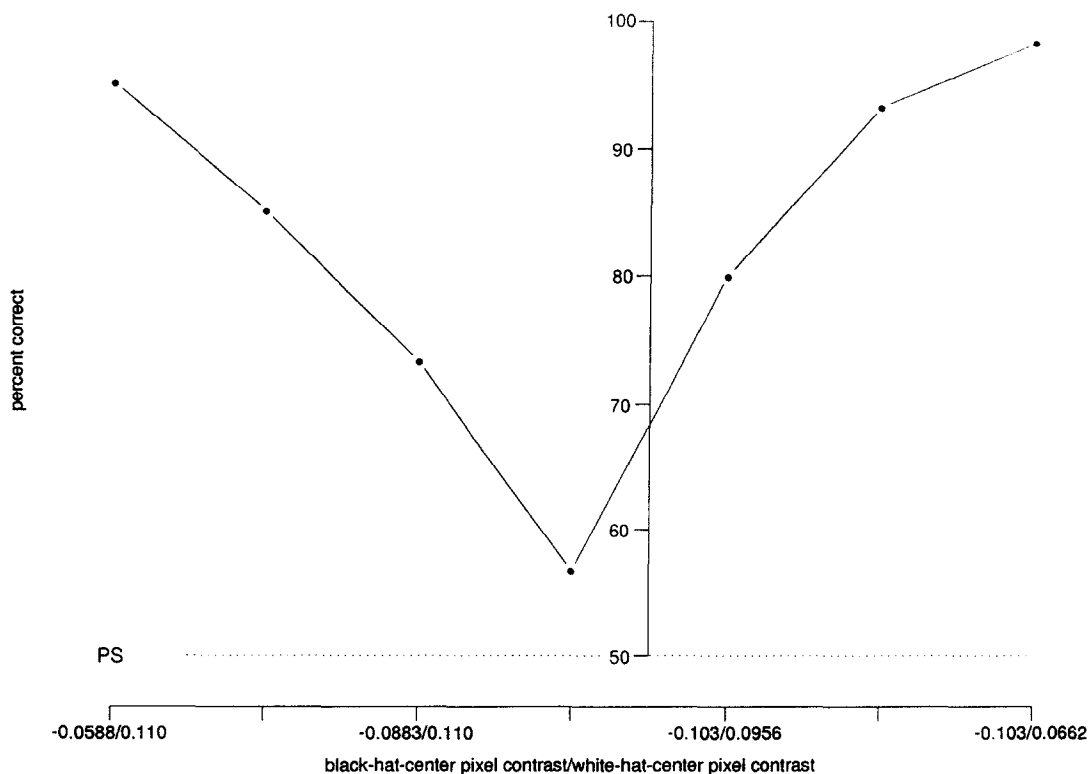


FIGURE 4. Accuracy of direction discrimination in half-wave stimuli as a function of the ratio of black-hat-center pixel contrast to white-hat-center pixel contrast. Data are from one subject. The ordinate is placed at a ratio $-1/1$. Each data point is the average of 60 trials. The horizontal dotted line indicates chance performance. The lowest point on the curve indicates the contrast ratio yielding minimum full-wave contribution to direction discrimination in the half-wave stimulus. The ratio at the minimum, measured separately for each subject, was used for all subsequent half-wave stimuli viewed by that subject.

black-hat-center pixel contrast/white-hat-center pixel contrast ratio that yields the poorest direction discrimination performance is $-14/15$. This contrast ratio was used for all of the subsequent half-wave displays which he saw. For AH, this ratio was $-11/15$; for AKH, $-13/15$; for RK, $-14/15$; and for JS, $-4/5$.

Discussion

The performance of each subject was minimized when the black-hat-center pixel contrast was of a slightly smaller magnitude than the white-hat-center pixel contrast. This indicates that the black hats are slightly more effective stimuli than white hats for full-wave motion mechanisms. The result also demonstrates that physical calibration (i.e. luminance linearization) is not sufficient for constructing a stimulus that does not stimulate full-wave motion systems. A psychophysical calibration also is required.

The ratio minimizing full-wave stimulation may change as overall stimulus contrast increases. However, because the measured ratios were obtained at near-threshold contrasts, contrast invariance is not an issue for subsequent threshold measurements. Furthermore, Expt 2 will demonstrate that thresholds for half-wave direction discrimination are unaffected by Fourier and full-wave masks having contrast much greater than that which could be introduced by imprecision in either the physical or psychophysical calibration.

EXPERIMENT 2

When leftward and rightward moving components of the same type are presented in a composite stimulus, the resulting percept does not convey transparency; rather the display appears to flash in counterphase fashion. This indicates that both the leftward and rightward moving components excite the same pathways in the visual system and effectively cancel each other. Experiment 2 measures observers' sensitivities to half-wave, full-wave and Fourier stimuli. Specifically, we looked at the ability of each stimulus to mask the other two. If two components, moving in opposite directions, appear as such, then this is evidence that each stimulates a different motion-sensitive pathway.

Procedure

For each subject, nine psychometric functions were obtained. Initially, we measured direction discrimination performance for varying contrasts of half-wave, full-wave and Fourier stimuli (the *unmasked* stimuli). We then measured direction discrimination performance for each component of each composite stimulus where two of the above three stimuli were combined with random, independent directions of motion.

Psychometric functions for unmasked stimuli. For the unmasked stimuli, the 71% correct points on each psychometric function were estimated as before, using a staircase procedure (see Expt 1). Once the contrast value that produced 71% correct responses had been

estimated, the approximate location of the psychometric function on the contrast continuum was determined. Based on preliminary experiments, we decided to sample the psychometric function at seven specific points. Ideally, we would have sampled more points, but this would have taken too much time. Ultimately, the subject made 60 direction judgments for each contrast value.

Psychometric functions for masked stimuli. The following composite stimuli were tested: full-wave + Fourier (fw + f), half-wave + Fourier (hw + f), and half-wave + full-wave (hw + fw). For each composite stimulus the contrast of the first component grating, the *constant component*, was held constant at a value where direction discrimination was very good but not perfect. This value was determined by the results of the measurements for the unmasked stimuli, and differed for each subject. The second component grating was termed the *variable component*.

As before, in order to determine where to collect the main data of the experiment, we first estimated the 71% correct direction discrimination rate for each component

of every composite stimulus. In those cases where the subject's task was to report the direction of motion of the constant component, the staircase procedure applied to the contrast of the variable component. It was raised after two successive correct responses and lowered after every incorrect response. Given the staircase thresholds, the six composite psychometric functions were obtained in 24 consecutive sessions of 140 trials each.

Results: unmasked stimuli

Figure 5 displays the psychometric functions for the unmasked stimuli. Each row of graphs contains the data from one subject, each column contains the data from one stimulus. The data are quite consistent between subjects. If we take the point at which the psychometric functions cross 75% correct as an index of threshold, we find the following threshold ranges: For Fourier stimuli, 0.00478–0.0175, for full-wave stimuli, 0.0361–0.1225, for half-wave stimuli, 0.120–0.357. With sufficient contrast, all subjects can perform direction discrimination perfectly for all three types of stimuli.

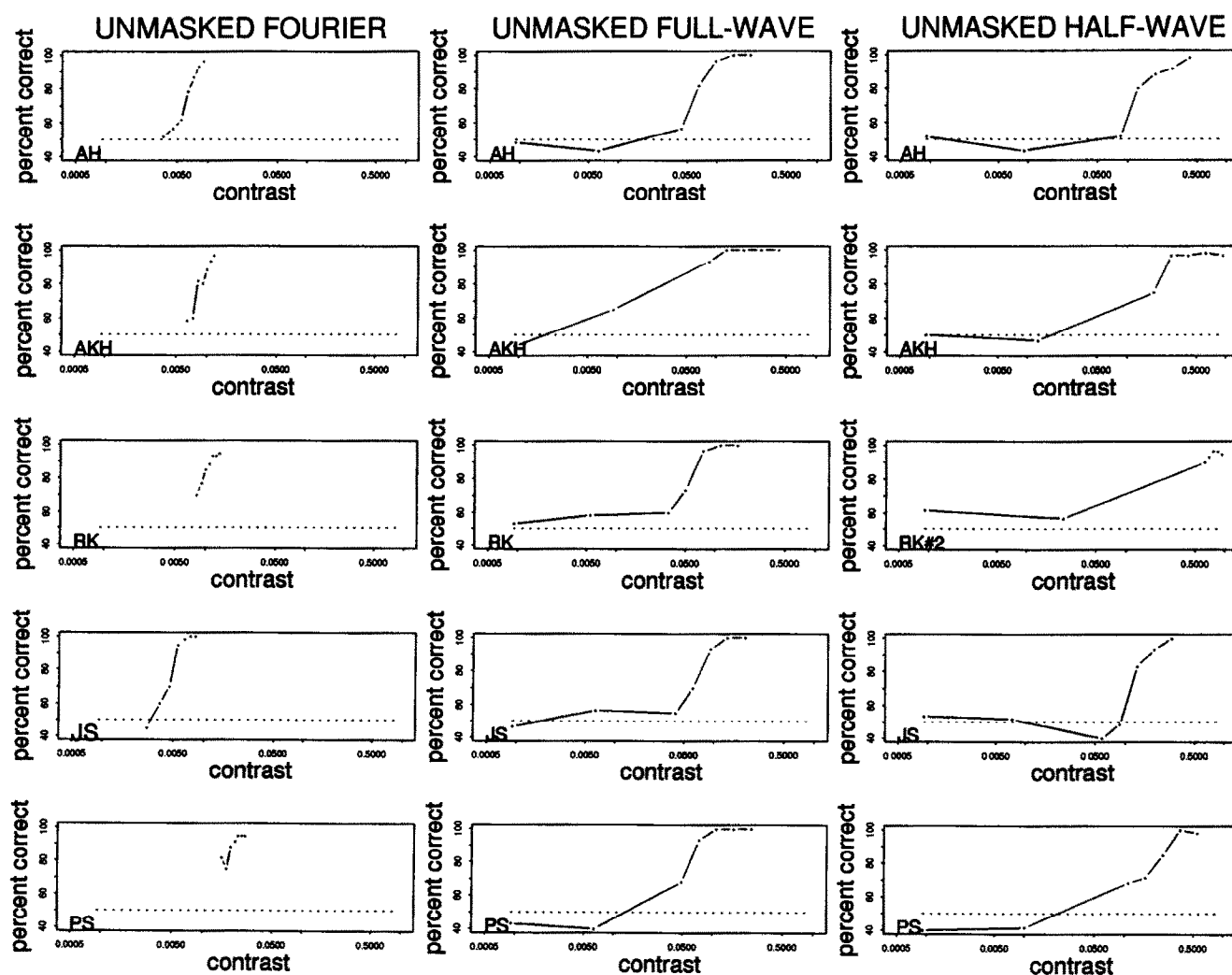


FIGURE 5. Psychometric functions for three types of stimulus and five subjects. Each row of panels represents a different subject, each column a different type of stimulus. Column header indicates stimulus type. Within panels, the abscissa indicates stimulus contrast. The ordinate indicates the percent correct left/right direction discriminations, the horizontal dotted line indicates chance performance (50%). Each data point is the average of 60 trials.

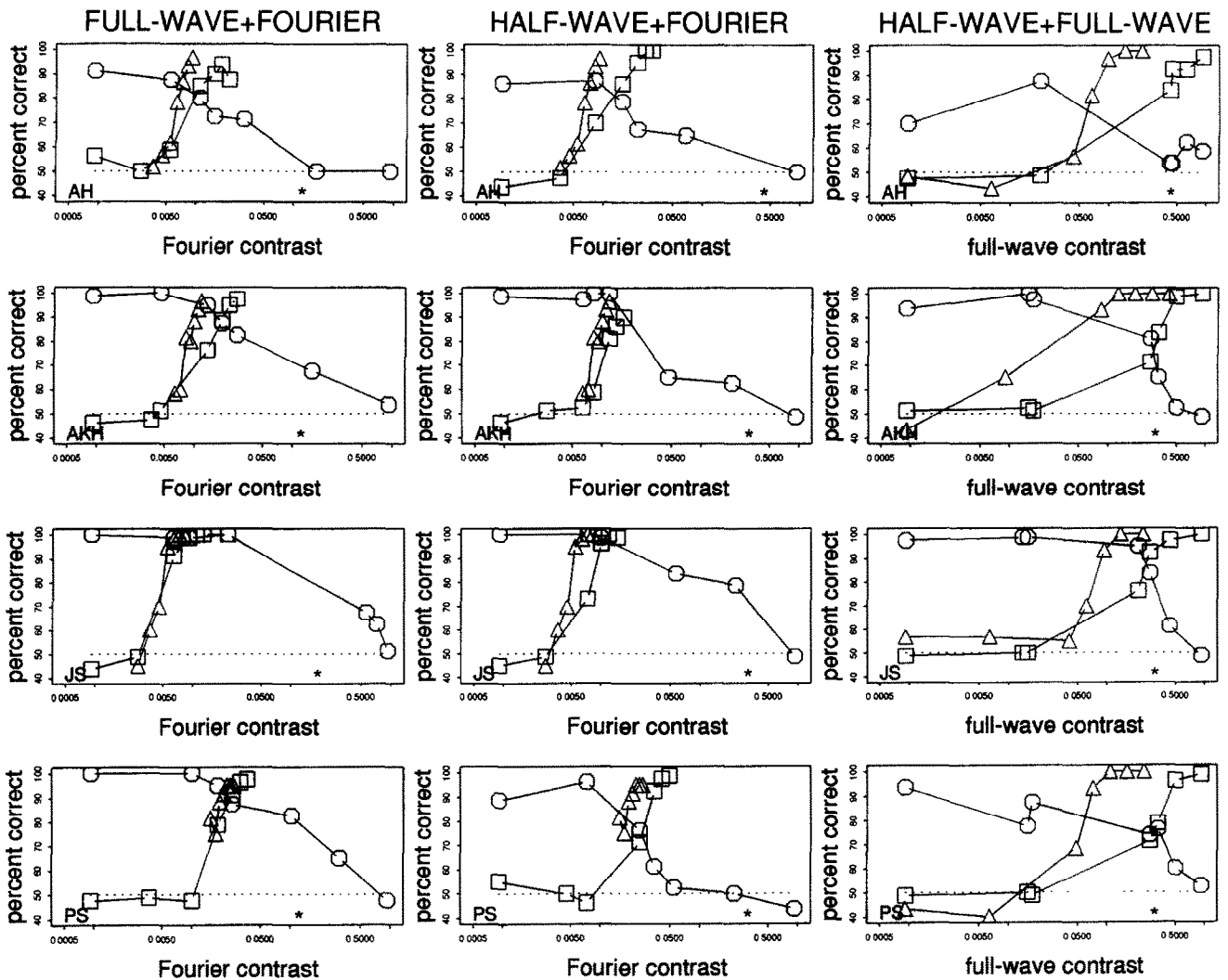


FIGURE 6. Direction discrimination in composite stimuli. Rows and columns as in Fig. 5. Each data point is the average of 84 trials. The left column of graphs shows performance with full-wave + Fourier composites, as a function of the contrast of the Fourier components. The contrasts of the full-wave components are indicated by asterisks above each abscissa. Triangles indicate the psychometric function for unmasked Fourier stimuli (as in Fig. 5). Squares represent trials in which the subject indicated the direction of the Fourier (full-wave) component in a composite stimulus. The octagons indicate direction reports of the full-wave component of the composite. Center column: discrimination in half-wave + Fourier composites as a function of the contrast of the Fourier components. The contrast of the half-wave component is indicated by asterisk above each abscissa. Triangles indicate direction discrimination of unmasked Fourier stimuli, squares indicate masked Fourier components, octagons indicate masked full-wave components. Right column: discrimination in half-wave + full-wave composites as a function of the contrast of the full-wave components. The contrast of the half-wave components is indicated by an asterisk above each abscissa. Triangles indicate direction discrimination of unmasked full-wave stimulus. Squares indicate masked full-wave components, octagons indicate masked half-wave components.

One subject, RK, finished the unmasked portion of Expt 2 but required a contrast of 0.77 to achieve a performance level greater than 96% correct for the unmasked half-wave stimulus. This high threshold made it physically impossible to produce appropriate stimuli for the masking phase of the experiment so, at this point, she was excused from the remainder of the experiment. All the other data obtained in Expt 2 are displayed in Fig. 6.

Results: dual motion stimuli

Full-wave masking Fourier. The leftmost panels of the figure show the psychometric functions for the unmasked Fourier stimulus (triangles), the Fourier

stimulus with a full-wave mask (squares), and the full-wave stimulus with a Fourier mask (octagons). The superposition of the triangle and square points in Fig. 6 (left panels), for subjects JS and PS means that their ability to discriminate between opposite directions of Fourier motion is unaffected by a simultaneous full-wave motion stimulus that has greater contrast, random direction, and exhibits perfectly visible motion. For the other two subjects, the full-wave stimulus interferes slightly but significantly with Fourier direction discrimination.

Fourier masking full-wave. Although full-wave motion is impaired by Fourier motion masking, subjects continue to make above-chance full-wave direction

discriminations even when the contrast of the Fourier mask is more than 10 times its own threshold contrast.

Simultaneous visibility of full-wave and Fourier motion. For subject JS, who was well practiced when he ran these sessions, there is a 2.5-fold range of Fourier contrasts (0.0092–0.023) for which direction discrimination of either component of the composite stimulus is essentially perfect. That is, for composite stimuli in this range, when subject JS is asked the direction of Fourier motion, he answers perfectly, and on other trials, when he is asked about the full-wave motion, he answers perfectly. The other subjects AH, AKH and PS had no practice before running these sessions. For these four subjects, there is at least one Fourier contrast value for which performance on each component is greater than or equal to 80% correct. Thus, in a stimulus that contains independent full-wave and Fourier motions, upon request, subjects can accurately report the direction of either component.

Masking: half-wave and Fourier. The center column of panels of Fig. 6 shows the psychometric functions for the unmasked Fourier stimulus (triangles), the Fourier stimulus with half-wave mask (squares), and the half-wave stimulus with Fourier mask (octagons). The psychometric functions for the unmasked and half-wave-masked Fourier stimulus are quite similar, although all subjects show a slight masking effect. The masking effect of the half-wave stimuli (center panels) seems to be bigger than that of the full-wave stimuli (left panels). This is because the contrasts of the half-wave and full-wave stimuli were adjusted to produce equal performance, and this required much higher contrasts for the half-wave stimuli. However, given that the half-wave and full-wave stimuli yield equal direction discrimination, the masking effect of simultaneous Fourier motion stimuli is quite similar in both cases. That is, the decline in masked performances of the drift-balanced stimuli with increasing Fourier contrast (curves defined by octagons) is quite similar in the left and center panels.

Simultaneous visibility: half-wave plus Fourier. With half-wave + Fourier (as with full-wave + Fourier) there is a range of Fourier contrasts for which accurate performance on each component is possible. Again, there are several contrast combinations for which performance of JS on either component is perfect. For AKH, there is a small range of Fourier contrast for which performance on the half-wave component is perfect, and performance on the Fourier component is better than 80% correct. For AH and PS, the masked half-wave and masked Fourier curves appear to cross at roughly 80% correct and 75%, respectively.

Masking: full-wave and half-wave. The rightmost graphs of Fig. 6 show the psychometric functions for the unmasked full-wave stimulus (triangles), the full-wave stimulus with half-wave mask (squares), and the half-wave stimulus with full-wave mask (octagons). As opposed to the Fourier/drift-balanced combinations, the combination of two drift-balanced stimuli produces large mutual interference effects. Nevertheless, with sufficient contrast, the full-wave stimuli overcome half-wave

masking, and subjects do achieve near-perfect performance.

The rightmost panels of Fig. 6 contain no examples of composite stimuli in which subjects can perfectly judge the direction of motion of each component. This is especially noteworthy for subject JS for whom there were wide contrast ranges of Fourier plus drift-balanced composite stimuli (Fig. 5, center and left columns, row 3) in which perfect judgments of either motion component were possible. Subject JS's masked half-wave and full-wave curves appear to cross at approx. 85% accuracy. Similarly, for subjects AH and AKH, the masked full-wave and masked half-wave curves cross at a lower accuracy level than do the masked full-wave and masked Fourier curves or the masked half-wave and masked Fourier curves. For PS, both the masked half-wave and masked Fourier curves and the masked half-wave and masked full-wave curves cross at approx. 75%, a level far below that at which the masked full-wave and masked Fourier curves cross. The 75% level is significant because, in a task in which the chance level is 50%, 75% represents the performance level that would be achieved when one task is performed perfectly but the other task is at chance.

The horizontal position at which the half-wave + full-wave curves cross is also significant. As opposed to the curves in the full-wave + Fourier graphs, those in the half-wave + full-wave graphs cross relatively close to the points on the abscissae indicated by the asterisks. This is true for all subjects, even though AH's exact half-wave + full-wave crossing point cannot be accurately determined from the data. This indicates that in order for a half-wave grating to mask the motion of a full-wave grating, the half-wave grating's contrast must be only slightly less than that of the full-wave grating.

Interpreting opposite-direction trials in full-wave plus half-wave stimuli. Figure 7 shows data from the subset of trials in which the half-wave and full-wave components moved in different directions. These data are approximately symmetric about the 50% line that represents chance performance: accuracy for one component is above chance, the other below. These data, and introspective observations, are accounted for by two principles. (1) When the components of approximately equal perceptual strength move in opposite directions, subjects recognize this but they are utterly unable to link the components to the directions. (2) When one component is very much stronger than the other, subjects report that both components move in the direction of the stronger component.

Optimal dual performance. Additionally, in each of the panels of Fig. 7, near the place where the curves cross, there are a few points for which the mean performance for each of the motion stimuli lies slightly but significantly above the chance line. The subjects' perception of these stimuli is that of motion transparency: two stimuli appear to be moving in opposite directions. But the subjects do not know which direction of motion to assign to which stimulus (half-wave or full-wave). The data suggest that the subjects' guesses about the

assignment of direction of motion to the stimuli may be slightly better than chance. Subjects JS and PS were able to perform significantly above chance in both tasks at one particular full-wave contrast each. Otherwise, no subject at any contrast level was able to perform above chance in both tasks. We conclude that simultaneous discrimination of the direction of motion of our full-wave and half-wave stimuli is nearly always impossible, and in those exceptional conditions where it does occur, it is very weak.

Discussion

Separate drift-balanced and Fourier channels. If the motions of our half-wave and full-wave stimuli were perceived due to imprecision in luminance linearization, then Fourier masking should be extremely detrimental to direction discrimination of these stimuli. In fact, we will show below that thresholds for our drift-balanced stimuli are unchanged in the presence of masks that are an order of magnitude greater than the possible level of any such distortion product. The reverse is also true: Fourier components can be identified in the presence of large amounts of full-wave and half-wave masking. Such paired observations would be expected if there were indeed separate mechanisms for the detection of drift-balanced and Fourier motion. The fact that there are composite stimuli for which either the direction of a Fourier

component or the direction of a drift-balanced component can be correctly determined strongly suggests that, at some point in the visual system, the motion of each component is carried by a separate pathway. Since the motion signals of each type of grating have the same wavelength and speed, we conclude that the separate pathways are qualitatively different: not just scaled replicas of each other.

Separate half-wave and full-wave channels. The results for the half-wave + full-wave composite are not so easy to interpret. However, one thing is clear: even with considerable full-wave masking contrast (contrast > 0.25), observers are able to determine the direction of the half-wave component grating accurately. These observations rule out that direction discriminability of the half-wave grating might have been due to full-wave pollution, i.e. that our psycho-physical calibration of Expt 1 was imprecise. The contrast step size in the calibration experiment was on the order of 1%. Suppose that there had been an error of half a step in achieving perfect balance, resulting in a residual full-wave signal on the order of 0.5% contrast. The full-wave masks that admit simultaneous half-wave direction discrimination are on the order of 10–100 times greater contrast than any possible full-wave artifact. Hence we rule out the possibility that half-wave direction discrimination is based on artifactual full-wave signals, and conclude that direction discriminability of the half-wave

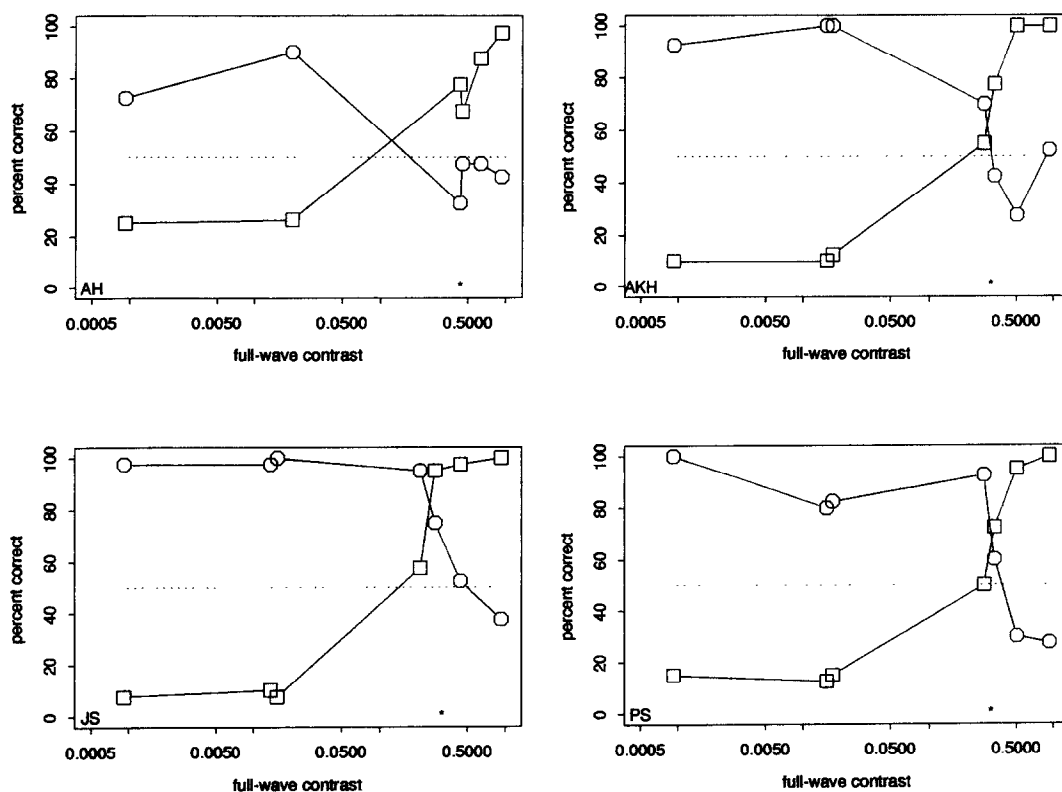


FIGURE 7. Direction discrimination performance with half-wave + full-wave composites on trials in which the two components moved in opposite directions. Squares indicate performance on the full-wave components, octagons indicate performance on half-wave components. These data are a subset of those shown in the right column of graphs in Fig. 6. For most composites, subjects were able to perform above chance (indicated by the dotted lines) for only one of the two components.

grating is due to a mechanism which does not depend on full-wave rectified input.

When the full-wave and half-wave components moved in opposite directions, subjects were unable to link each stimulus with its direction of motion. This result, together with the result that half-wave motion can be reported in the presence of significant full-wave masks, suggests that the outputs of a half-wave and a full-wave motion-mechanism are similar, even though the motion-extraction computation itself is quite different. There is an exceptional observation with a particular half-wave + full-wave stimulus for which JS was able to correctly identify the direction of the half-wave grating on 84% of the trials and the full-wave grating on 92% of the trials. This proficiency would have been impossible if JS had used exactly the same resources to process both half-wave and full-wave directional information. By our definition of a mechanism, which is consonant with other motion-extraction mechanisms so far proposed (e.g. Adelson & Bergen, 1985; van Santen & Sperling, 1984; Watson & Ahumada, 1985), a single mechanism cannot simultaneously signal opposite directions—motion in opposite directions is perceived as counterphase flicker. Therefore we conclude that, on a significant portion of trials, JS demonstrates an ability to access two different mechanisms for processing full-wave and half-wave stimuli.

Subjects report that when the half-wave and the full-wave components had similar contrast and moved in opposite directions, they perceived transparent motion but could not determine which grating moved which way. This report is at odds with the notion that the motions of both half-wave and full-wave gratings are extracted by the same mechanism. In such a scheme, we would expect leftward full-wave and rightward half-wave motions to cancel each other. For example, in an informal demonstration, we were able to show that bi-directional half-wave + full-wave composite stimuli are trivially discriminable from counterphase flickering half-wave + full-wave composites. We postulate that subjects' poor performance in the half-wave + full-wave conditions reflects an inability to appropriately label a motion percept as "half-wave" or "full-wave". Experiment 3 (below) was designed to further characterize the perceptual systems for half-wave and full-wave analysis.

Relative Efficiency Analysis of Threshold Stimuli

How efficient are we at determining the direction of half-wave and full-wave stimuli, relative to an ideal motion detector that receives the same receptor information? To answer this question *absolutely*, we would have to make numerous assumptions about the nature of the detector (e.g. point-spread function, receptor density, etc.) and count the average number of quanta each type of stimulus produces for each type of detector. A much simpler computation is *relative* efficiency analysis, which ignores quantal statistics and considers only total contrast energy. Contrast energy is

$$\int_{x,y} c(x, y, t)^2 dx dy.$$

In our stimuli, each frame has the same contrast energy so the t can be ignored. The square of contrast (rather than the absolute value) is appropriate to our assumptions about the effectiveness of the hat stimuli in selectively stimulating either on-center or off-center systems (Solomon *et al.*, 1993). There it was assumed that, because of a (possibly soft) threshold in the half-wave and full-wave transducers, the surround pixels were relatively much less effective than the center pixel. This assumption is consistent with a square-law rectifier but not with an absolute-value rectifier.

Method

Because all of our stimuli are the same wavelength, move at the same speed and have the same mean luminance, the only relevant stimulus parameter on which they differ to an ideal detector is in the amount and location of contrast energy.

Half-wave contrast energy. Our half-wave stimuli (Fig. 2) consist of random textures of black and white hats. Compared to Fourier gratings (Fig. 2) with the same contrast, the half-wave gratings contain only one-eighth as much contrast energy. The reader can arrive at this fraction as follows: for this calculation we regard hats as 3×3 pixel arrays. Let c denote the (peak pixel) contrast of both stimuli, Let N denote the number of hats in a half-wave stimulus. The energy contributed by the hat centers h_c is given by

$$h_c = Nc^2. \quad (1)$$

The contrast of each pixel in the hat surrounds is $\pm \frac{1}{8}c$. Since there are eight pixels in each hat surround, the energy they contribute h_s is given by

$$h_s = 8N\left(\frac{1}{8}c\right)^2. \quad (2)$$

The total contrast energy in a half-wave stimulus is thus

$$h_c + h_s = Nc^2 + \frac{1}{8}Nc^2 = \frac{9}{8}Nc^2. \quad (3)$$

Since there are 9 times as many pixels in a Fourier grating as there are hats in a half-wave grating, each with pixel contrast $\pm c$, the total contrast energy in a Fourier stimulus f is thus

$$f = 9Nc^2 = 8(h_c + h_s). \quad (4)$$

Hence half-wave stimuli contain one-eighth as much contrast energy as equal-contrast Fourier stimuli.

Full-wave contrast energy. Our full-wave gratings contain one-quarter as many hats as the half-wave gratings. The remainder of the full-wave stimuli is non-informative uniform gray. Thus, when compared to half-wave and Fourier gratings with the same stimulus contrast, the full-wave gratings contain only $\frac{1}{4}$ and $\frac{1}{32}$ as much contrast energy, respectively.

Results

The data are taken from the unmasked psychometric functions that were measured in Expt 2 (Fig. 5). The

TABLE 1. Efficiency analysis of threshold stimuli

Stimulus	u		Fourier (f)	Full-wave (fw)	Half-wave (hw)
Peak pixel contrast at 0.75	c_u	AH	0.0063	0.0603	0.12
Direction discrimination threshold		AKH	0.008	0.0361*	0.187
		RK	0.009	0.0524	0.357*
		JS	0.0048	0.0683	0.121
		PS	0.0175	0.1225	0.185
Fraction of contrast energy w.r.t. Fourier stimulus	w_u		1	1/32	1/8
Relative efficiency	$w_u c_u^2 / c_f^2$	AH	1	0.344	0.0217
		AKH	1	1.570*	0.0146
		RK	1	0.937	0.0050*
		JS	1	0.157	0.0125
		PS	1	0.654	0.0716
Mean relative efficiency (excluding asterisks)			1	0.523	0.0301

*Threshold estimates are unreliable.

75% correct thresholds were estimated by linear interpolation.

Relative efficiency. The relative efficiencies of the mechanisms which detect half-wave, full-wave and Fourier motion can be determined by comparing threshold squared contrasts for each type of stimulus, weighted by the proportion of contrast energy in stimuli of equal contrast. Table 1 contains 75%-correct thresholds for each observer and each stimulus. In two instances, AKH full-wave and RK half-wave, the 75% correct thresholds are relatively poorly determined by the data (see Fig. 5). Asterisks in Table 1 indicate the unreliability of these threshold estimates.

Excluding the two poorly determined efficiencies from further analysis, Table 1 shows that the observers are 0.16–0.94 times as efficient at determining the direction of the full-wave stimulus as they are at determining the direction of the Fourier stimulus. When determining the direction of the half-wave stimulus, observers are 0.012–0.072 times as efficient, compared to when they determine the direction of the Fourier stimulus.

Discussion

Contrast thresholds for full-wave gratings invariably are many times higher than thresholds for Fourier gratings. For example, in Expt 2, the average ratio was 9.2:1. Therefore, it is surprising to discover that the efficiency for determining the direction of full-wave gratings was, on average, 52% of the efficiency for determining the direction of Fourier gratings. The efficiency computation shows that the apparent insensitivity to full-wave gratings is mainly due to the objectively lower information in the stimulus rather than to a weakness of full-wave motion perception relative to Fourier. Indeed, the high efficiency for full-wave gratings suggests that the full-wave computation is not an incidental property of the visual system but one that has evolved and specialized. On the other hand, the relatively much lower efficiency for half-wave gratings and the fact that only about one-third of the population achieves even this modest level of performance, suggest that

half-wave direction discrimination has much less evolutionary value than Fourier or full-wave direction discrimination.

Full-wave detection does not use half-wave channels. There are two arguments: (1) insufficient sensitivity of a half-wave mechanism, and (2) insensitivity of the full-wave system to half-wave masks. In support of (1), previously it was noted that temporal differentiation, followed by half-wave rectification, of our full-wave gratings can produce residual, veridical motion signals. Assuming that all of the signal energy contained in a threshold full-wave grating could be utilized by a motion detector receiving *half-wave* rectified input, that energy would constitute only a fraction of the total required by that detector for threshold direction discrimination. Specifically, that fraction is given by the relative efficiency for half-wave direction discrimination with respect to full-wave direction discrimination. On average, that fraction is 0.084. In other words, our efficiency calculations demonstrate that threshold full-wave gratings contain only 8% of the signal energy required for half-wave direction discrimination.

In support of (2), the results of Expt 2 indicate that unless a half-wave grating has nearly as much contrast (i.e. nearly 4 times the signal energy) as a full-wave target, masking will not occur. Any full-wave spillover into half-wave channels would be orders of magnitude smaller and overwhelmed by half-wave masks of even moderate contrast. Therefore, we conclude that any half-wave byproducts in our full-wave stimuli are inconsequential.

EXPERIMENT 3

For each subject, the presence of a moving half-wave mask appears to interfere with direction discrimination of full-wave targets. (The interference manifests as a rightward shift of the masked curves, relative to the unmasked curves in Fig. 6.) To a lesser extent, drift-balanced masks also appear to interfere with Fourier direction discrimination. Does this interference occur at

the level of motion detection (in which one motion detection mechanism interferes with another) or some earlier level of processing (in which the mere presence of pixel contrast in half of the display is sufficient to interfere with motion that is defined by the pixels in the other half)? Experiment 3 was designed to answer this question.

In Expt 3, we compared direction discrimination performances on a target grating with a moving mask, and the same grating with a non-moving (counterphase) mask of the same energy. The counterphase mask has the contrast and the flicker of the moving mask, but it does not produce a perception of directional motion. If a mask does not have to move in order to be effective as a mask, the nonmoving, counterphase grating will be as effective a masker as the moving grating. Counterphase masking equal to motion masking would provide evidence that the motion-masking effect is due to interference at a stage of processing prior to motion extraction rather than to the interference of two different motion processes.

Procedure

Three of the four subjects of Expt 2 participated in Expts 3 and 4; subject AKH was unavailable. In each session, two psychometric functions (test threshold as a function of mask contrast) were measured concurrently by a mixed-list procedure. To determine the motion-masking psychometric function, we used precisely the same stimuli as in Expt 2. To determine the counterphase masking function, the masking stimuli underwent a 180 deg phase shift (instead of 90 deg) in every frame-block. Thus, instead of moving, the mask appeared merely to flicker.

The temporal frequency of the counterphase stimulus was twice the frequency of the moving stimulus for the following reason. Because the stimuli were square-wave functions of time, a counterphase stimulus at the same spatial and temporal frequency as the moving stimulus remains unchanged for a full half-cycle, whereas the moving stimulus changes every quarter cycle. Preliminary observations indicated that direction discrimination occurs relatively unimpaired during the quarter cycle in which the counterphase grating remains unchanged, and is masked only by the temporal changes in the other quarter cycle.

Direction discrimination of the test stimuli as a function of mask contrast was determined for both counterphase and moving masks. In other respects, procedure was the same as in Expt 2.

Results

Figure 8 displays the psychometric functions for the stimuli with moving and counterphasing masks. Each row of graphs contains the data from one subject, each column contains the data from one stimulus. The left column of panels in Fig. 8 shows the psychometric functions for the full-wave target with a moving Fourier mask (octagons) and the full-wave target with a counterphasing Fourier mask (crosses). Similarly, the central

and right columns show the psychometric functions for the half-wave targets with Fourier masks and for half-wave targets with full-wave masks. For each subject, in each viewing condition, the two psychometric functions appear to have similar shapes. For JS and PS, in each viewing condition, the function obtained with a counterphasing mask appears to be a small rightward shift of the function obtained with a moving mask, indicating a decreased masking when a moving mask is replaced with a counterphasing mask. The only exception is AH's performance in the full-wave + Fourier condition, in which the function obtained with a counterphasing mask appears to be a small *leftward* shift of the function obtained with a moving mask.

Discussion: apportioning the masking effect

Estimating the total amount of masking. The extent of the horizontal shift between psychometric functions obtained with moving and counterphasing masks is an indication of the contribution of motion to the mask's effectiveness. We estimate the extent of horizontal shift as follows. For each subject and each viewing condition, we calculate the single non-increasing function that represents the shapes of both psychometric functions. Since the procedure yielded measurements at the same mask contrasts for both psychometric functions, the best fitting function is simply the set of lines connecting the means of the two measurements at each mask contrast. (When necessary, a relaxation algorithm was used to enforce monotonicity.) We then calculated two horizontal positions of the best-fitting function, one which minimized its squared vertical distances from each of the two sets of data points. The lateral difference between these two positions is an estimate of the shift between the two psychometric functions.

Nine shifts were estimated; three for each subject. The shifts varied from -0.36 to 0.65 log base 10 units in magnitude, with a mean of 0.23 log units. The negative shift arises from the full-wave + Fourier condition for subject AH, where overall performance was slightly better with the moving mask than with the counterphasing mask. The largest rightward shift occurred in the half-wave + Fourier condition for subject AH. It had a magnitude of 0.65 log units.

We conclude that, on the average, the motion component's contribution to the mask's effectiveness is 0.23 log units. Adding motion is equivalent to increasing the masking contrast by 0.23 logs, or by a factor of 1.70 . The factor is greater for Fourier masks and smaller, perhaps zero logs, for full-wave masking of half-waves.

Apportioning the amount of masking to contrast flicker and to motion per se. Of the total 1.70 units of masking produced by a moving stimulus, 1.00 is the masking that would be produced by a counterphase flickering grating and 0.70 is the additional amount produced by a moving stimulus. Therefore we say that $0.7/1.7 = 0.41$ is the fraction of masking effect that is caused by motion and the remainder 0.59 is the fraction caused by contrast flicker. However, because the square-wave stimuli required the counterphase mask to have twice the

temporal frequency of the moving masks, the fraction of nonmotion masking is probably underestimated.

EXPERIMENT 4

For composite stimuli composed of half-wave and Fourier components, or full-wave and Fourier components or half-wave and full-wave components, the results of Expts 2 and 3 indicate that, given the proper relative stimulus contrasts, observers are able to accurately determine the direction of motion of either moving component. This suggests that at some point in the visual system, full-wave rectifying, half-wave rectifying and standard motion pathways are all separate. Yet, if attention could be used to selectively suppress or enhance activity in a given pathway, it is conceivable that a single motion analyzer could receive input from any two or all three of the above pathways. Experiment 4

was designed to determine whether or not Fourier, full-wave and half-wave motion detection compete for attentional resources.

Procedure

For each subject, we measured direction discrimination performance using the same composite stimuli as before. This time, immediately preceding every trial, the subject was randomly given one of six instructions—four “attention” instructions and two “control” instructions. Subjects ran 84 trials with each instruction on each composite stimulus.

Instructions

Each instruction was conveyed by a unique combination of tones. There were two *control conditions*: (1) report only the direction of component A; and (2) report only the direction of component B. There were four

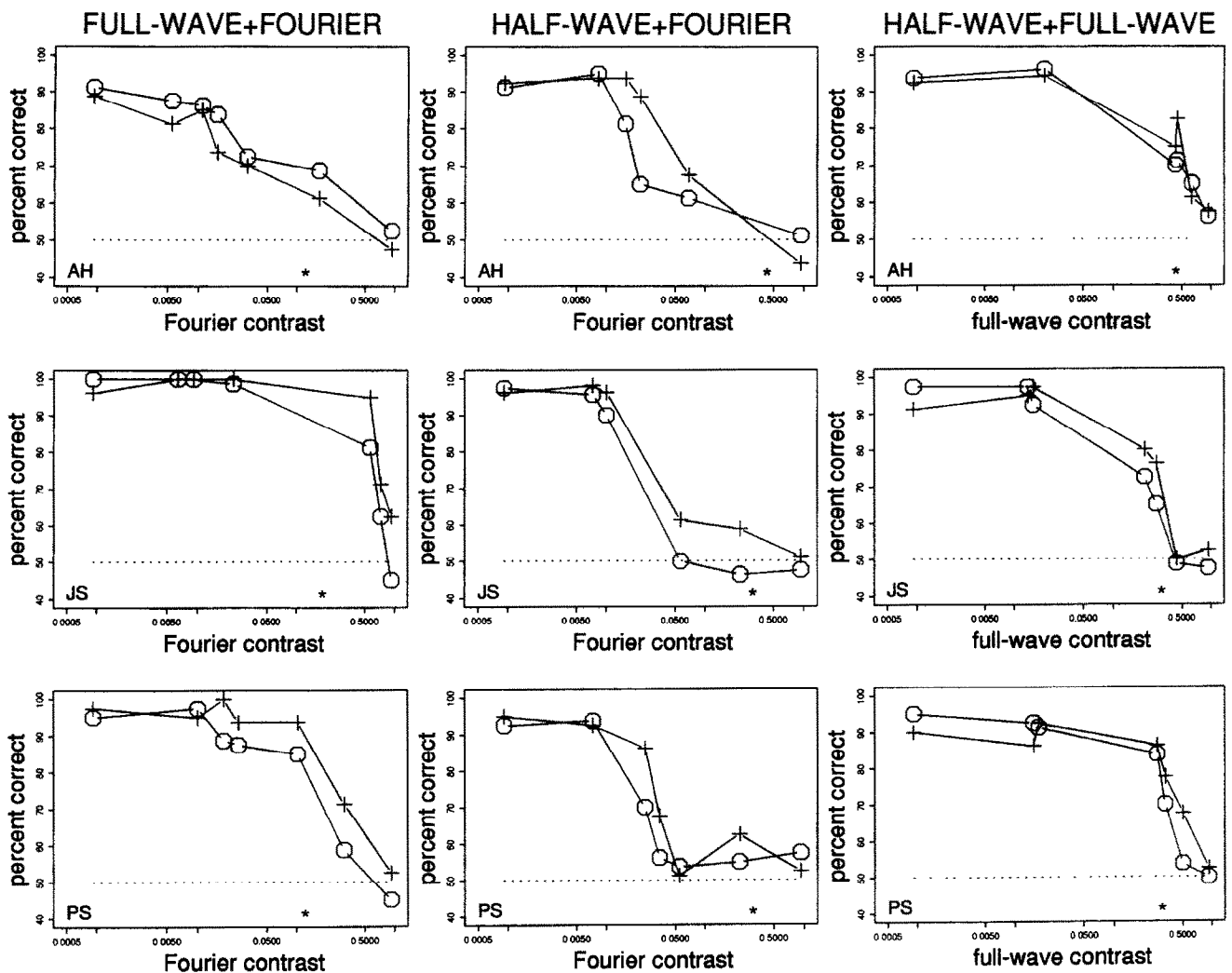


FIGURE 8. Direction discrimination performance in presence of moving and nonmoving masks. The left column of graphs shows performance with full-wave + Fourier composites, as a function of the contrast of the Fourier components. The contrasts of the full-wave components are indicated by asterisks above each abscissa. Center column: direction discrimination in half-wave + Fourier composites as a function of the contrast of the Fourier components. The contrast of the half-wave component is indicated by asterisk above each abscissa. Right column: direction discrimination in half-wave + full-wave composites as a function of the contrast of the full-wave components. The contrast of the half-wave components is indicated by an asterisk above each abscissa. Composite stimuli in which the masking component moved are indicated by octagons; counterphase flickering (non-moving) masks are indicated by crosses.

attention conditions: (1) attend to component A, report the directions of both components, starting with component A; (2) attend to component B, report the directions of both components, starting with component B; (3) divide attention equally, report the directions of both components, starting with component A and (4) divide attention equally, report the directions of both components, starting with component B.

Payoffs

Subjects were also informed that they would be reimbursed in accordance with their performance. In addition to a base rate, they would earn 10 points for every correct answer when there was a single tone instruction. For the trials where they were to divide their attention equally, each correct answer was worth 5 points. For the remaining trials, correctly identifying the direction of the to-be-attended component was worth 8 points and a correct response for the other component was worth 2 points. Subjects were indeed paid at a bonus proportional to their total number of points, which they monitored at the end of every block of trials.

Stimuli

For each subject, the two components which comprised each composite stimulus had the same contrasts on every trial. Specifically, we used those contrasts which, in Expt 2 had yielded the most similar performances on the two tasks with masked stimuli. For example, with a 0.0156 contrast Fourier grating and a 0.436 contrast half-wave grating, AH achieved 86% accuracy on the Fourier grating and 79% accuracy on the half-wave grating (upper left panel in Fig. 6). Therefore we used these contrasts in Expt 4. AH's data from half-wave + full-wave condition in Expt 2, did not yield any measurements in the region where the masked full-wave and half-wave curves crossed. In this one case, we estimated the full-wave contrast that would have coincided with this crossing.

Results

The results of Expt 4 are plotted in Fig. 9 as attention operating characteristics (AOCs, Sperling & Melchner, 1978). Each row of panels contains the data from one subject, each column contains the data from one type of composite stimulus. In each panel, the ordinate indicates the accuracy of identifying the direction of one component and the abscissa indicates the accuracy of identifying the direction of the other. The data from the control trials, in which the subject was required to report the direction of a single component, are graphed adjacent to the appropriate edge of the panel. Dotted lines normal to the axes project from these control points and terminate at their intersection. This intersection, the "independence point", represents the performance that would be attained if the subject could perform as well in the experimental conditions (in

which two directions of motion were reported) as in the control conditions (in which only one report was required).

Data from trials in which the subject was required to divide attention equally between the two components are represented by a single point on each graph. Solid lines connect the equal-attention point to points which describe performance in the two other attention conditions, in which the subject was instructed to attend differentially to a specific component.

The bottom row of Fig. 9 shows the data collapsed across subjects. In the average data, the overall trends in the data are quite apparent. All the data—from equal and from selective attention trials—fall close to the independence point. There certainly is no evidence that selective attention improves direction discrimination of the attended component. Indeed, the only suggestion of any effect of selective attention is a slight tendency for an overall benefit for attention to the drift-balanced component of a Fourier/drift-balanced composite and to the half-wave component in the full-wave/half-wave composite. There seems to be a corresponding very small tendency for overall impaired performance when the other component is attended. To reiterate, these are very slight effects, and they do not indicate any selective advantage for the attended stimulus component (see Sperling & Doshier, 1986).

Discussion

If attention were required to determine the direction of motion of a particular component of a composite stimulus, then we should have found a selective advantage for the attended component. No such advantage was found. The clustering of the dual-task data at the independence point means that observers are able to report the directions of both the target and the mask just as accurately when asked to report them simultaneously as when asked to report them alone in control conditions. There appears to be no important effect of selective attention. Consequently, we conclude that selective attention does not play a major role in these experiments.

(a) The results of Expt 2 show that, at some point in the visual system, the path-ways that process Fourier, full-wave and half-wave motion are pairwise separate (because two different directions of motion are discriminable in composite stimuli). (b) The results of Expt 4 show that there are adequate resources to process two kinds of stimuli in parallel without loss relative to a single stimulus. That is, the dual motion processing was *data limited* not *resource limited* (Norman & Bobrow, 1975).

GENERAL DISCUSSION

When Chubb and Sperling (1989) reported that a single display could simultaneously stimulate both Fourier and non-Fourier based motion percepts, they did not draw a distinction between separate mechanisms and separate pathways leading to the same

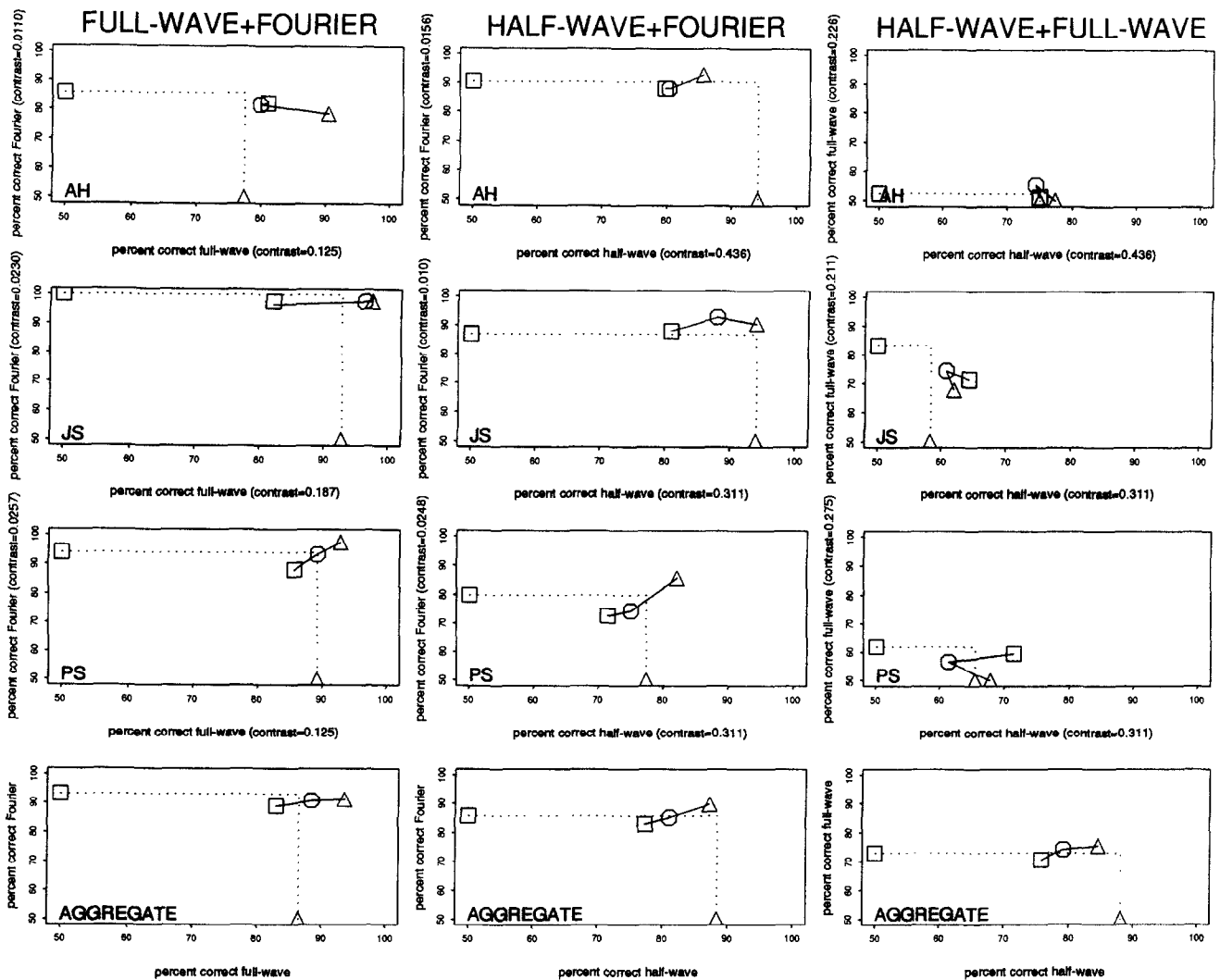


FIGURE 9. Attention operating characteristics for the three types of composite stimuli. The panels in a row represent data from a single subject or, in the case of the last row, the average data of the three subjects. The panels in a column represent data obtained with a particular type of composite stimulus. Within each panel, the abscissa represents accuracy of direction discrimination of one component of the composite stimuli, the ordinate represents direction discrimination accuracy of the other component. Performance on trials in which the subjects were instructed to report the direction of just one of the components are indicated adjacent to the appropriate coordinate by points connected to dotted lines normal to the coordinate. Data from trials in which subjects were to report the directions of both components are shown in the three symbols connected by solid lines in each graph: circle, equal attention; square, selective attention to component represented on ordinate; triangle, selective attention to component represented on abscissa. Data points close to the independence point (the intersection of dashed lines) indicate that the two concurrent direction discrimination tasks do not share attentional resources.

mechanism. This distinction is diagrammed in Fig. 10(a, b). The current experiments indicate that observers perceive square-wave and drift-balanced gratings of identical spatial and temporal frequency to move transparently. These results are at odds with the notion that there is only a single motion extraction mechanism; they require that there be at least two motion-extraction mechanisms. Similarly, our subjects report that full-wave and half-wave stimuli appear to move transparently. Again, we propose that there are separate mechanisms capable of extracting full-wave and half-wave motion. Experiment 3 showed that the clearly visible *motion* of a full-wave masking component in a composite stimulus hardly interfered with half-wave motion detection. This independent detection of full-wave and half-wave motions further sup-

ports the notion of separate motion-extraction mechanisms.

However, in Expt 2, and in subsequent observations, we found that when full-wave and half-wave components move in opposite directions, subjects were unable to determine which component was which. We conclude that the outputs of the full-wave and half-wave mechanisms are not differently labeled. These observations are summarized in Fig. 10(c).

Finally, it is very interesting to note that the full-wave motion system is almost as efficient at extracting motion as the Fourier system. There must be good reasons why it evolved to this advanced state, but the present experiments do not address this issue. However, it is quite likely that synthetic vision systems may similarly benefit from incorporation of a full-wave computation.

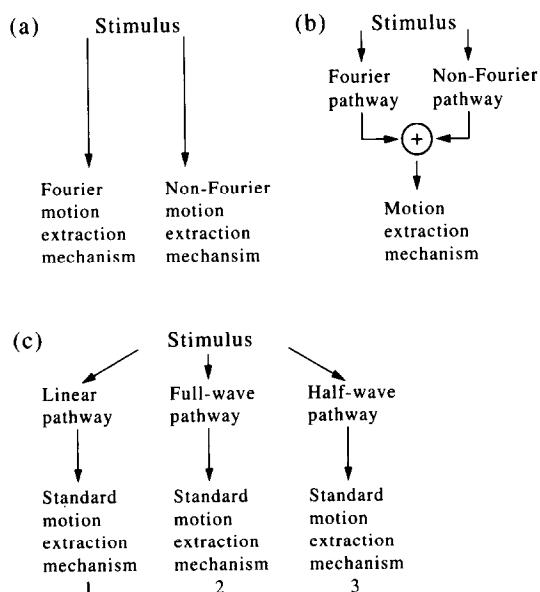


FIGURE 10. Schemes for motion extraction. (a) Separate Fourier and non-Fourier motion extraction mechanisms. (b) The outputs of separate Fourier and non-Fourier pathways combine at the same motion extraction mechanism. (c) Three separate and independent mechanisms extract motion. Each pathway contains spatio-temporal linear filters. The full-wave pathway additionally contains a full-wave rectifier, and the half-wave pathway contains a half-wave rectifier. The outputs of these pathways are processed by three separate and independent standard motion analysis mechanisms.

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