Pergamon

PII: S0042-6989(97)00040-0

Vision Res., Vol. 37, No. 17, pp. 2381–2399, 1997

Printed in Great Britain
0042-6989/97 $17.00 + 0.00

Perception of Motion Direction in Luminance- and Contrast-defined Reversed-phi Motion Sequences

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Received 27 September 1996; in revised form 15 January 1997

Nonlinear processing can be used to recover the motion of contrast modulations of binary noise patterns. A nonlinear stage has also been proposed to explain the perception of forward motion in motion sequences which typically elicit reversed-phi. We examined perceived direction of motion for stimuli in which these reversed motion sequences were used to modulate the contrast of binary noise patterns. A percept of forward motion could be elicted by both luminance-defined and contrast-defined stimuli. The perceived direction of motion seen in the contrast-defined stimuli showed a profound carrier dependency. The replacement of a static carrier by a dynamic carrier can reverse the perceived direction of motion. Forward motion was never seen with dynamic carriers. For luminance- and contrast-defined patterns the reversed motion percept increasingly dominated, with increases in the spatial frequency and temporal frequency of the modulation. Differences in the patterns of responses to the two stimuli over spatial and temporal frequency were abolished by the *addition* of noise to the luminance-defined stimulus. These data suggest the possibility that a single mechanism may mediate the perception of luminance- and contrast-defined motion. © 1997 Published by Elsevier Science Ltd.

Motion Reversal First-order Second-order Reversed-phi

INTRODUCTION

The spatio-temporal Fourier transform of a rigidly moving pattern has components which are constrained to lie on a line or plane through the Fourier domain origin (see Fleet & Langley, 1994). This is not the case for non-rigid motion patterns, often referred to as second-order (Cavanagh & Mather, 1989), which include the motion of texture boundaries and the motion of contrast modulations of static or dynamic carriers. Although we can see motion in such patterns, the recovery of second-order motion has proved difficult for standard motion analysis (Chubb & Sperling, 1988), as there may be no energy lying on the plane in Fourier space corresponding to the velocity of the second-order signal.

How does the visual system deal with these second-order patterns? It has been proposed that a nonlinearity inherent in the visual transduction process may introduce distortion products into the signal at the spatial frequency of the second-order components (Burton, 1973; Nachmias & Rogowitz, 1983). However, in the motion domain, evidence against the distortion product hypothesis is provided by Ledgeway & Smith (1994) and Mather & West (1993). They constructed stimuli that consisted of interleaved first- and second-order motion sequences. The distortion products in the second-order frames should combine with the first-order frames to give an unambiguous sense of movement; however, no consistent direction of motion was seen. In a direct test of the distortion product hypothesis, Badcock & Derrington (1989) showed that the perceived motion of a drifting beat could not be nulled by the addition of a signal designed to cancel the distortion product. It would appear that the distortion product hypothesis cannot adequately account for the perception of second-order motion.

An alternative to the proposal that all signals are distorted by early nonlinearities is that the visual system contains a channel incorporating an explicit nonlinear stage (Chubb & Sperling, 1989a; Sperling, 1989; Wilson *et al.*, 1992). We can summarize models which propose the recovery of second-order motion by a separate processing stream in the following manner: in addition to a linear "Fourier" channel there is a grossly nonlinear "non-Fourier" channel based on a fullwave rectification-like process (Sperling, 1989; Lu & Sperling, 1995a). There may be additional nonlinear channels (Chubb *et al.*, 1994; Solomon & Sperling, 1994) and the Fourier

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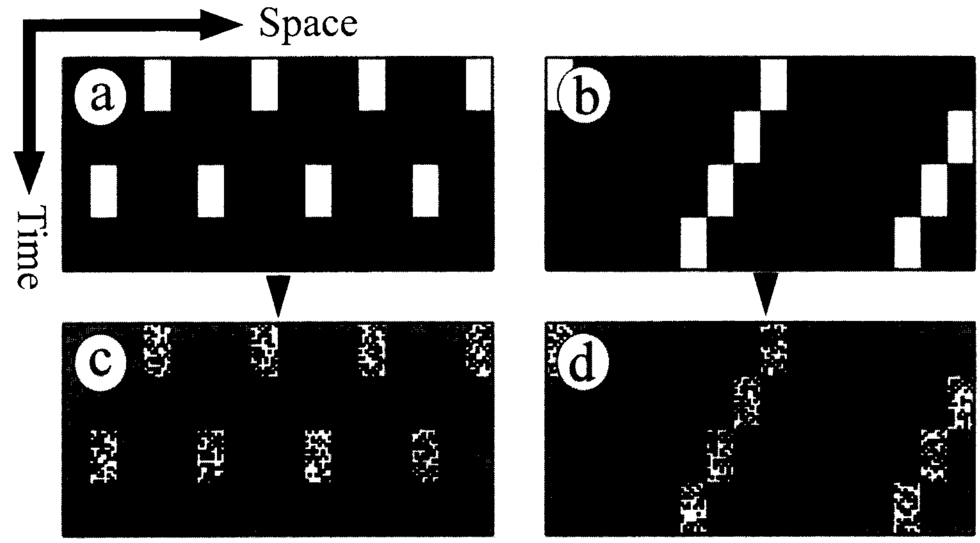

FIGURE 1. Space–time plots showing: (a) Γ_L stimulus; (b) Φ_L stimulus; (c) Γ_C stimulus; (d) Φ_C stimulus.

channel itself may contain some distortion product (Scott-Samuel & Georgeson, 1995). In the non-Fourier pathway the nonlinearity is preceded by oriented bandpass spatial filtering, with filters tuned to a range of spatial frequencies (Chubb & Sperling, 1991; Langley *et al.*, 1996; Sutter *et al.*, 1995). An initial temporal filtering stage has also been proposed, which may involve both bandpass and lowpass filters (Chubb & Sperling, 1989b, 1991).

Whilst the low level detection of motion is thought to be based upon combining the results of local spatio-temporal filtering operations, another vein of research suggests the existence of a high level feature tracking mechanism (Cavanagh, 1992); this may be identified with the long range process (Braddick, 1980). Smith (1994) suggests that this mechanism exists side by side with the first- and second-order mechanisms. Lu & Sperling (1995b,c) also provide evidence that they interpret as confirming the existence of this tripartite architecture. They put forward the theory that tracking is accomplished by mapping features onto a saliency map, which is then subject to standard motion energy analysis.

Studies of reversed apparent motion have been considered to provide evidence for a nonlinear channel. Reversed apparent motion was first identified and investigated by Anstis (1970). If the contrast of the second frame is reversed in a two-frame apparent motion sequence, then a strong percept of motion is obtained in the direction opposite to the displacement. Chubb & Sperling (1989a) describe a stimulus, referred to as Γ, consisting of a cyclic pattern of bars which steps forward a quarter of a cycle every frame and concurrently reverses contrast polarity [see Fig. 1(a)]. Chubb and Sperling report that subjects see the stimulus moving in the *forward* direction when close to the stimulus, but see it moving in the *reversed* direction when they move further from the stimulus. They propose that this phenomenon is indicative of a two-channel architecture for low level vision. The reversed motion percept is identified with the linear channel and the forward motion percept with the nonlinear channel. However, this change in perceived direction can also be interpreted as resulting from the scale-dependent behaviour of a single motion mechanism (Johnston *et al.*, 1992; Johnston & Clifford, 1995a). Gorea (1995) has also examined perceived motion direction in contrast reversing stimuli, and has shown that forward motion begins to predominate as the temporal and/or spatial frequency of the stimulus decreases.

Chubb & Sperling (1988) describe a class of stimuli which they refer to as micro-balanced. Contrast modulated random noise provides an example of this type of stimulus. Since motion energy analysis does not provide a coherent response for micro-balanced stimuli, any perceived motion in such a stimulus is attributed to activity in the non-Fourier channel. It is possible to generate a second-order analogue of a first-order motion stimulus by modulating the contrast of binary noise instead of modulating luminance. As the aim of processing in the second-order channel is the recovery of the modulant, the output of the nonlinear stage of the second-order channel should resemble the pattern used to modulate the noise. This signal would then be subjected to motion energy analysis. We can ask what subjects would see if presented with a contrast-defined version of the Chubb & Sperling (1989a) stimulus [Fig. 1(c)]. A two-channel model would predict that no motion energy should be detected by the Fourier channel. Motion mechanisms in the second-order channel should signal reversed motion. The perception of forward motion would require further explanation in the form of an additional rectification-like process or an additional mechanism based on some other principle.

Reversed apparent motion has been shown to occur with contrast reversing random dot kinematograms (Sato, 1989). Using a second-order analogue of this stimulus (a "random window kinematogram") Nishida (1993) demonstrated that reversed motion could be elicited by a non-Fourier stimulus. Mather & Murdoch (1996) constructed a second-order version of a "four stroke" contrast reversing stimulus (Anstis & Rogers, 1986) and reported that subjects see continuous motion in the direction opposite to the displacement. Two studies (Sperling & Lu, 1996 and Benton *et al.*, 1996) have used contrast-defined versions of the Chubb & Sperling (1989a) stimulus. Both studies found reversed motion, but Sperling and Lu additionally found that motion in the forward direction could be elicited when stimuli were presented at low temporal frequencies and viewed in the fovea. Sperling and Lu explain the motion reversal as evidence for two separate motion systems. The second-order channel is identified as signalling reversed motion. A feature tracking mechanism is invoked to explain the perception of forward motion.

Second-order motion detection mechanisms seek to extract the modulant whilst attempting to discard the carrier. It is, therefore, of interest to determine whether the characteristics of the carrier influence the perception of motion direction. In this study we examine perceived motion direction in first- and second-order contrast-reversing motion sequences over a range of temporal and spatial frequencies. We also investigate the influence of the form of the carrier on perceived direction of motion in second-order stimuli.

METHOD

Equipment and display

Images were displayed on a non-interlaced monochrome Manitron monitor (P31 phosphor), driven by a Matrox Image-1280 graphics card controlled by an IBM compatible PC. The graphics card delivered 8 bits per pixel to give 256 grey levels. The display was carefully gamma-corrected using a Minolta LS-110 luminance meter and was spot checked using a UDT OPTOMETER S370. All of the sequences generated and displayed in this study were 32 frames long. The frame rate was 59.5 Hz. In each trial the screen around the stimulus was set to mean luminance and the full screen reverted to mean luminance between trials. Stimuli were displayed in a vertically oriented rectangle positioned in the centre of the screen. From a viewing distance of 1 m the screen had a width of 20.80 deg and a height of 16.67 deg. The stimuli used in this study stepped forward 1/4 cycle every stimulus frame. The temporal frequency of the stimulus is dependent upon the number of physical frames per stimulus frame. For example, if there are four physical frames per stimulus then the temporal frequency is 3.75 Hz. The direction of displacement was either upwards or downwards.

Experiment 1. Gamma-corrected space–time images were constructed in PC RAM and passed to the graphics card. Data was loaded, frame by frame, from the space–time image into an output look-up table, which was indexed by a ramp drawn in display memory. The image was displayed in a rectangle centred in the middle of the screen. From a viewing distance of 1 m the rectangle had a width of 12.55 deg and a height of 14.59 deg. Mean luminance (I_0) was 15.4 cd/m^2.

Experiments 2–8. Gamma-corrected frames were generated in PC RAM and stored on the graphics card. The rectangle within which stimuli were displayed had a width of 8.40 deg and a height of 12.54 deg. Mean luminance (I_0) was 14.8 cd/m^2. As many of the image sequences in these experiments used two-dimensional spatial patterns, far more information has to be stored on the graphics card than is the case when one-dimensional images are used (i.e., Experiment 1). Because of the limited amount of graphics memory available, the "images" on the graphics card were scaled up four times for display on the screen. Each "stimulus pixel" therefore consists of 4×4 "physical pixels", where a physical pixel is one of the 1280×1024 picture elements available on the monitor.

Stimuli

Luminance-defined stimuli. Two basic sets of stimuli were constructed: a polarity reversing bar stimulus, described as "Γ" by Chubb & Sperling (1989a) and shown in Fig. 1(a), and a comparison stimulus. This comparison stimulus, a Φ motion sequence, is shown in Fig. 1(b) and is a set of light and dark forward stepping bars. Both of these stimuli step forward 1/4 cycle each stimulus frame. These images consist of three intensity levels, I_{max}, I_0, and I_{min}, where I_0 is the mean luminance. The relationships between the three luminance levels may be described in the following way:

$$I_0 = (I_{max} + I_{min})/2, \ (\text{where } I_{max} \geq I_{min})$$

Stimulus contrast is defined by the following equation:

$$\text{Contrast} = (I_{max} - I_{min})/(I_{max} + I_{min})$$

Contrast-defined stimuli. The envelopes used to modulate luminance were also used to modulate the contrast of various types of binary random noise. This was done such that, in the subsequent image, areas of maximum luminance became areas of maximum contrast (C_{max}), areas of medium luminance became areas of medium contrast (C_0), and areas of low luminance became areas of low contrast (C_{min}). Each contrast region consisted of two luminance levels as detailed below:

$$C_{max} : I_0 \pm k_{max} \ C_0 : I_0 \pm k_0 \ C_{min} : I_0 \pm k_{min}$$

where

$$k_0 = (k_{max} + k_{min})/2, (k_{max} \geq k_{min}).$$

The standard Michelson contrast of each region is given by

$$C_x = k_x/I_0.$$

The relationship between the three contrast levels may be described by

$$C_0 = (C_{max} + C_{min})/2,$$
$$(\text{where } C_{max} \geq C_{min} \text{ and } C_0 = 0.5).$$

For the purposes of this study, modulation depth is defined as

$$\text{Modulation Depth} = (C_{max} - C_{min})/(C_{max} + C_{min}).$$

Space–time plots of the contrast-defined stimuli are

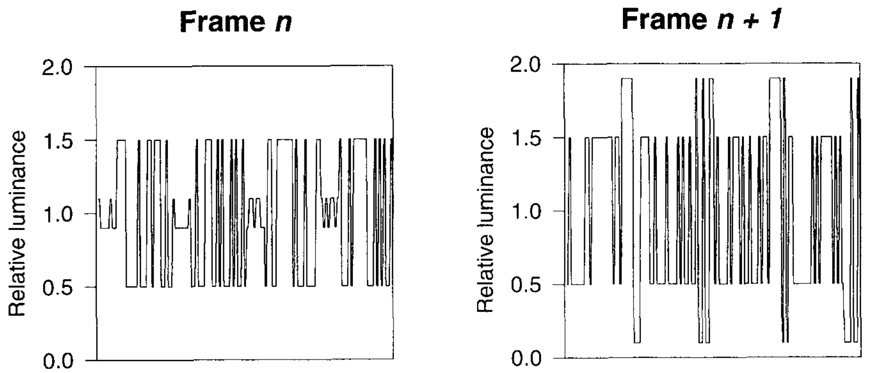

FIGURE 2. Luminance cross-sections from successive stimulus frames of a Γ_C stimulus with a dynamic noise binary noise carrier. Luminance is given in multiples of mean luminance.

shown in Fig. 1(c, d); cross-sections of the luminance profiles from two frames of the contrast-defined Γ stimulus are shown in Fig. 2. Given the equations above and the mean luminance (I_0) used in the experiments, the majority of the stimuli used this study can be characterized by their contrast (in the case of luminance-defined stimuli) or modulation depth (in the case of contrast-defined stimuli). The exceptions occur when stimuli contain additive noise. In these cases, details of the stimulus before noise has been added and the amplitude of the noise provide a characterization of the stimulus. Where it is not obvious from the context, contrast-defined stimuli are marked as such by a subscripted "C" (i.e., Φ_C and Γ_C). Luminance-defined stimuli are indicated by a subscripted "L" (i.e., Φ_L and Γ_L).

Binary random noise. The contrast-defined stimuli used in this study are modulations of binary random noise. Four types of binary random noise are used: static one-dimensional (1D) noise, dynamic 1D noise, static two-dimensional (2D) noise and dynamic 2D noise. Figure 3 shows four frames from Γ_C stimuli with these four carrier types.

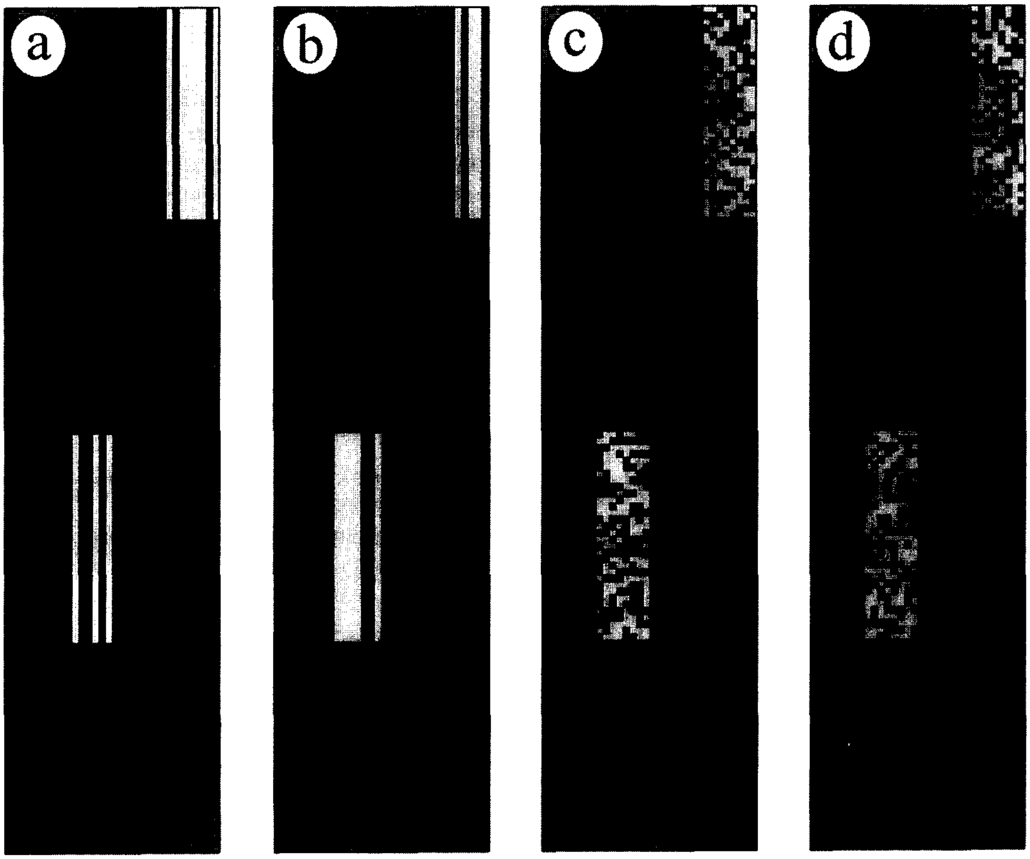

FIGURE 3. Four successive stimulus frames from a Γ_C stimulus with the following carriers: (a) 1D static noise; (b) 1D dynamic noise; (c) 2D static noise; (d) 2D dynamic noise.

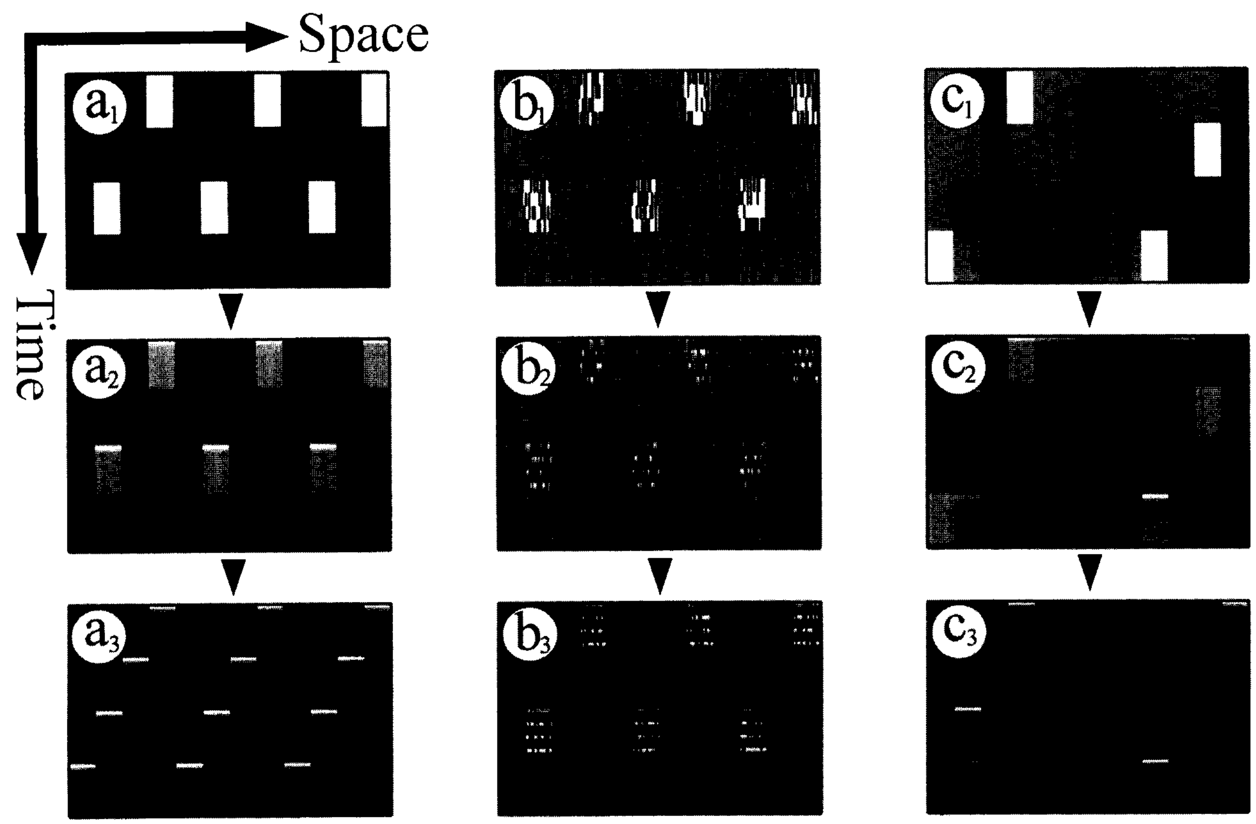

FIGURE 4. Space–time plots of a Γ_L stimulus (a_1), a Γ_C stimulus with a point noise carrier (b_1) and a Φ_C stimulus with a block noise carrier (c_1). The results of "best of both worlds" temporal filtering upon these stimuli are shown in a_2, b_2 and c_2. The results of rectification on the temporally filtered images are shown in a_3, b_3 and c_3.

Procedures

All subjects used in this study had normal or corrected to normal vision. Subjects were asked to fixate in the centre of the monitor screen and judge whether stimuli were moving upwards or downwards. The middle of the screen was approximately at eye level and the screen was the only source of illumination. There was a minimum gap of 1 sec between trials. In all the experiments described in this study, subjects were presented with a number of different stimulus types. In all but Experiment 1, these stimulus types were randomly interleaved. In Experiment 1 the stimuli were presented in blocks of one type; the order of presentation of the blocks was randomized across subjects. The direction of displacement and the start position of the bars were selected at random. In the Γ_L and Γ_C stimuli, the initial polarity of the modulant bar was also randomized. Effectively, all stimuli were stacked within an experiment, and a stimulus was randomly chosen from this stack for each trial. After a judgement had been made the stimulus was removed from the stack. Subjects indicated the perceived direction of motion using the up/down arrows on a PC

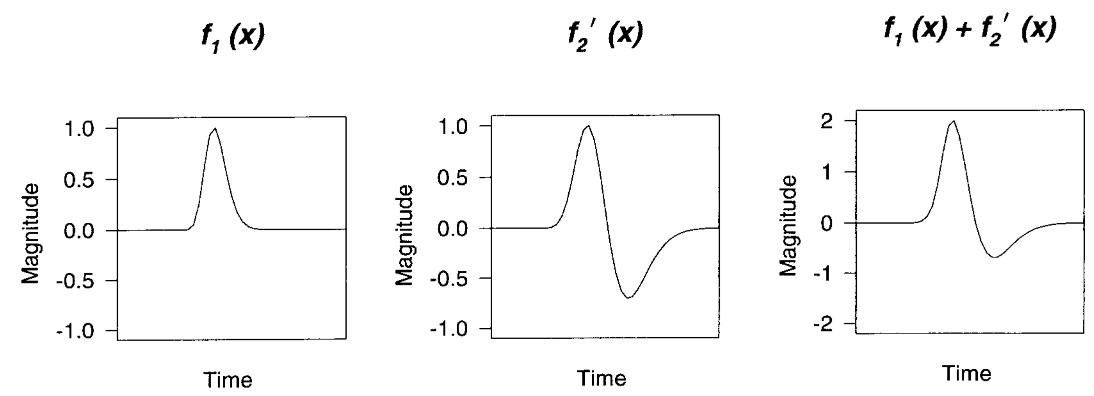

FIGURE 5. A "best of both worlds temporal filter" created from the sum of a log Gaussian ($f_1(x)$) and the differential of a log gaussian ($f_2'(x)$). The underlying standard deviations are different in order to closely approximate the functions presented by Chubb & Sperling (1989b).

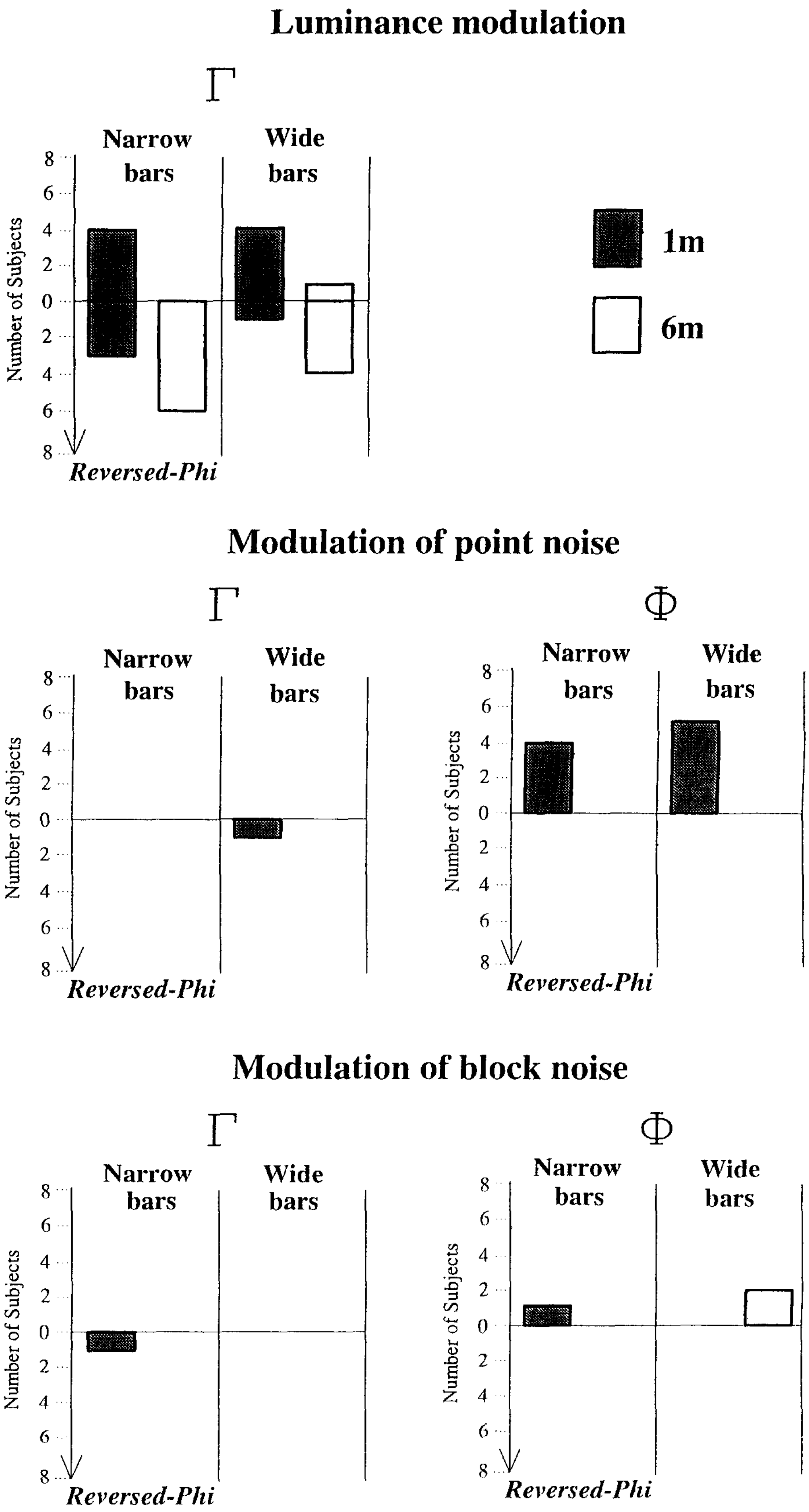

FIGURE 6. Numbers of subjects perceiving forward and reversed motion for luminance modulations and contrast modulations of point noise and block noise. Forward motion is indicated by bars above the x-axes, reversed motion is signalled by those below.

TABLE 1. Mean number of forward responses across subjects for Γ_L stimuli and Γ_C and Φ_C stimuli with point and block noise carriers

		Lum mod	Point noise		Block noise	
		Γ_L	Γ_C	Φ_C	Γ_C	Φ_C
Narrow bars	1 m	15.4	14.9	18.5*	14.1	17.8*
	6 m	5.9†	14.8	15.6	14.0	14.5
Wide bars	1 m	19.4	11.5†	21.0†	13.6	18.4†
	6 m	8.1	14.0	15.4	15.3	17.4

The maximum number of forward responses is 30 so the value expected if subjects responded randomly is 15. Numbers greater than 15 show a bias towards forward motion, numbers less than 15 show a bias towards reversed motion.

*Significant deviations from chance calculated by two-tailed t-test ($P < 0.05$).

†Significant deviations from chance calculated by two-tailed t-test ($P < 0.01$).

keyboard. If subjects suffered a lapse of attention on a particular trial they could restack the stimulus which they had just been shown by means of a key press. A fresh stimulus would then be randomly selected. This facility was seldom used.

RESULTS

The experiments described below investigate perceived direction of motion in luminance- and contrast-defined polarity reversing bars (Γ_L and Γ_C) and forward stepping bars (Φ_L and Φ_C). Space–time plots of the stimuli are shown in Fig. 1. The terms *forward* and *reversed* are used to describe perceived motion direction in both luminance- and contrast-defined stimuli. Forward motion is the direction in which the luminance/contrast bars move by 1/4 cycle. Reversed motion refers to a perception of motion in the direction opposite to the displacement. In the descriptions of stimuli presented below, the terms spatial and temporal frequency refer to the frequency of the modulant for both luminance- and contrast-defined patterns.

Experiment 1: preliminary investigations

Chubb & Sperling (1989a) explained the percept of forward motion obtained with their Γ_L stimulus by postulating a temporal filtering stage followed by a fullwave rectification-like nonlinearity. The initial temporal filter is the average of a lowpass filter and a bandpass filter. Figure 4(a) shows the effect of filtering and rectification on the luminance-defined Γ_L stimulus. In the filtering operations shown in Fig. 4 we used the average of a log Gaussian and the differential of a log Gaussian (see Fig. 5). In order to generate a filter which has a similar form to that used by Chubb & Sperling (1989a) we had to choose different time constants for the lowpass and bandpass filters. It is clear that the filtering and rectification operations allow the extraction of forward motion in the Γ_L stimulus.

Figure 4(b_1) shows an example of a contrast-defined Γ_C stimulus. A two-channel model would predict that no coherent motion energy would be detected in the Fourier channel, but that motion detectors in the non-Fourier channel would respond to a filtered and rectified version of the image [Fig. 4(b_3)]. Since this motion pattern is similar to a Γ_L stimulus, the stimulus should appear to move in the reversed direction.

In Fig. 4(c) the same image processing operations are applied to a Φ modulation of "block noise". The block noise is a 1D dynamic noise that has the same spatial and temporal extents as the bars making up the modulation. It is clear that filtering plus rectification can adequately recover the structure of the modulation signal. Subjects should have an unambiguous impression of forward motion in this case.

Eight subjects were tested over two different viewing distances; 1 and 6 m. In the following description all terms referring to the spatial dimension are given for the close viewing distance. Γ and Φ patterns were used to modulate dynamic 1D binary "point" noise, which was composed of elements with a width of 0.98 min and a temporal extent of 17 msec. In some conditions "point" noise [Fig. 4(b_1)] was replaced with "block" noise [Fig. 4(c_1)]. In this case the noise elements had the same temporal and spatial extents as the bars of the modulant. Subjects were also tested on luminance-defined Γ_L stimuli. At each distance, two bar widths were used, 0.16 and 0.33 deg, giving spatial frequencies of 1.52 and 0.76 cycles per degree, respectively. The temporal frequency of the stimulus was 3.75 Hz, which was the value used by Chubb & Sperling (1989a). The contrast of the luminance-defined stimuli was 0.9. The modulation depth for the contrast-defined stimuli was 0.8. Subjects were tested with all stimuli at both viewing distances. The order of presentation of classes was random and 30 members of each class were presented in succession. Half of the subjects were tested first at the near viewing distance, then at the far viewing distance. For the remainder the order was reversed.

Subjects made 30 responses to each class of stimulus. We recorded the number of responses indicating perceived motion in the forward direction. A score of 30 means that the subject responded in the forward direction on every presentation of that stimulus, whilst a score of 0 means that the subject responded solely in the reversed direction. A score of 15 indicates no overall bias towards perceiving motion in any direction. The binomial probability distribution gives the probability of n or more responses in a particular direction occurring by chance. A score of 21 or more, or 9 or less, can be taken as grounds for rejecting the hypothesis that the subject's performance is due to chance (on the basis of a two-tailed test and with 0.05 as the threshold probability). Figure 6 shows numbers of subjects reliably seeing motion in a particular direction for luminance-defined stimuli and for 1D dynamic point and block noise stimuli. Given the large number of measures, the probability of type I errors occurring is high. Conclusions can only reliably be drawn from the data when a number of subjects respond in the same manner and/or where some definite pattern emerges. We also compared mean responses across subjects for each condition. The results of this analysis are shown in Table 1.

Luminance-defined Γ stimuli. With this stimulus, at both viewing distances and both bar widths, the majority of subjects indicated consistent movement in a particular direction. Generally, the direction was not consistent across subjects. This lack of consistency in the perceived direction of motion is reflected in the group data. However, the findings are broadly consonant with those reported by Chubb & Sperling (1989a). At the closer viewing distance there was a greater tendency to see the stimulus moving in the forward direction, and conversely, at the further viewing distance there was a greater tendency to see motion in the reversed direction. As changing the spatial scale is similar to changing the viewing distance, one would expect a similar pattern of results to emerge with changes in scale to that seen with changes in viewing distance. Certainly, most subjects see forward motion when viewing the wide-bar stimulus at the near station point and reversed motion when viewing the narrow-bar stimulus at the further station point.

Modulations of 1D dynamic point noise. In general, subjects did not see a consistent direction of motion with Γ modulants. In isolated cases the results of single subjects achieved significance; however, given the number of subjects and the number of stimuli, this is certainly no more than would be expected by chance. The data provide no evidence to support the hypothesis that subjects perceived motion in any consistent direction when viewing these stimuli. This is not the case with Φ modulants. At the closer viewing distance these do elicit a reliable percept of forward motion. Increases in viewing distance substantially reduce this effect but there seems to be no reliable influence of bar width on the perceived direction of motion of the modulant. Results across subjects (Table 1) support the conclusions drawn from individual data.

With Γ_C stimuli, there is a small but significant bias in response towards the reversed direction in the group data for the lower spatial frequency at the short viewing distance. In pilot trials, using stimulus durations of 2 sec, subjects reported tracking the low contrast regions of Γ_C 1D dynamic point noise stimuli. It appears that, if tracking does occur, the probability of jumping from low contrast region to low contrast region in the space–time image may be differentially affected by the contrast of the intervening region. The presence of an intervening medium contrast region is less disruptive than that of an intervening high contrast region, leading to a bias towards the reversed motion percept. Given the small size of the bias, the lack of evidence that these stimuli produce a clear percept of motion in the single subject data, and the high probability of the occurrence of type I errors, it is likely that detection of motion of the Γ_C stimulus reflects some residual eye tracking.

Modulations of 1D dynamic block noise. Results within subjects [Fig. 6(bottom)] show that there is no strong percept of motion in any direction for both Γ_C and Φ_C stimuli. The results across subjects (Table 1) show no significant bias for Φ modulants. With the Φ_C stimuli there is some evidence for a small but consistent bias towards seeing motion in the forward direction.

The results for the present experiment can be summarized as follows:

1. The findings of Chubb & Sperling (1989a) are supported.
2. Whilst forward motion is seen in the Φ_C point noise stimuli, this is not the case with Γ_C point noise stimuli, where there is little evidence for any coherent motion percept.
3. In stimuli with 1D dynamic block noise carriers, there is little or no perception of coherent motion in any particular direction.

Whilst the findings of Chubb and Sperling are supported, the effect measured in the current experiment is comparatively weak. The most likely reason for this lies in the differences between the ranges tested. In the present experiment the smallest spatial frequency was 0.76 c/deg, and the largest was 9.15 c/deg. In Chubb and Sperling's experiment the spatial frequencies ranged from 1.56 c/deg to 12.5 c/deg. With a higher maximum spatial frequency it is probable that our results would match those of Chubb and Sperling.

The difference between Φ and Γ modulations of 1D dynamic point noise is more problematic. The lack of second-order reversed-phi would seem inconsistent with the findings of Nishida (1993) and indeed of Mather & Murdoch (1996) and Sperling & Lu (1996). However, the source of the difference may well lie with the type of carrier used in the present experiment. Smith *et al.* (1994) investigated the effects of carrier on detection and direction identification of modulations of binary noise carriers. The use of a 1D dynamic noise carrier appears to have a seriously detrimental effect on both types of threshold. If motion in Γ_C stimuli was intrinsically more difficult to detect than motion in Φ_C stimuli, then the difference found between these two types of stimulus might simply reflect a difference in threshold. If this is the case then second-order reversed motion may well be elicited by stimuli with carriers other than 1D dynamic noise. Based on the findings of Smith *et al.* (1994), static 1D or static 2D noise carriers would be the most likely candidates.

With both Γ_C and Φ_C patterns, the use of a 1D dynamic block noise carrier inhibits the perception of any coherent motion. This is surprising, given the effectiveness of

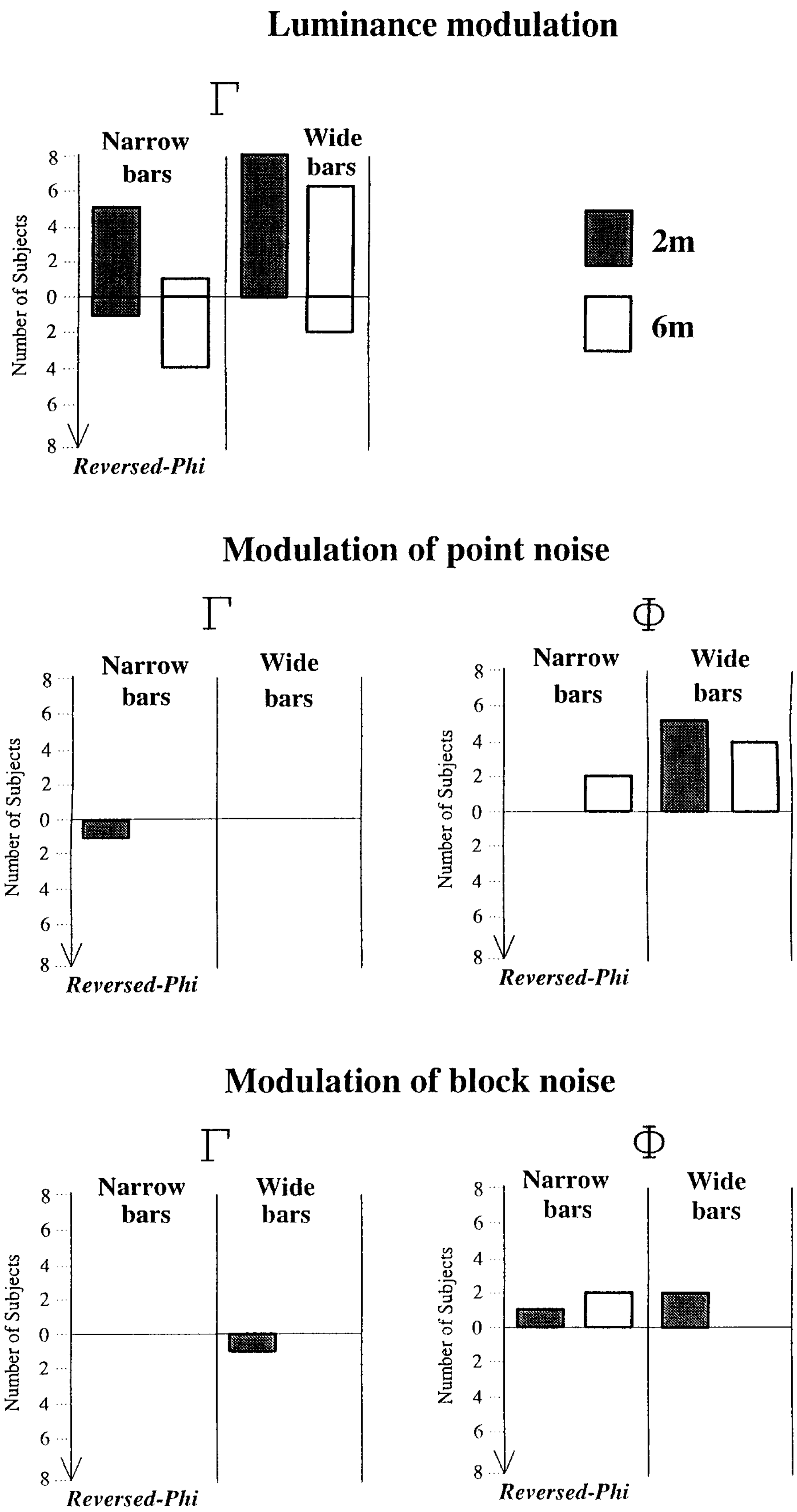

FIGURE 7. Results from the "oval window" experiment indicating numbers of subjects perceiving forward and reversed motion for luminance modulations and contrast modulations of point noise and block noise. Forward motion is indicated by bars above the x-axes, reversed motion is signalled by those below.

TABLE 2. Results from the "oval window" experiment, indicating the mean number of forward responses across subjects for Γ_L stimuli and Γ_C and Φ_C stimuli with point and block noise carriers

		Lum mod	Point noise		Block noise	
		Γ_L	Γ_C	Φ_C	Γ_C	Φ_C
Narrow bars	1 m	21.3	15.6	16.8	13.6	17.5*
	6 m	10.9	16.4	18.3	14.1	16.3
Wide bars	1 m	28.4†	13.4*	21.8†	12.5	19.1*
	6 m	18.4	14.5	20.5	14.1	15.9

The maximum number of forward responses is 30 so the value expected if subjects responded randomly is 15. Numbers greater than 15 show a bias towards forward motion, numbers lower than 15 show a bias towards reversed motion.

*Significant deviations from chance, calculated by two-tailed t-test ($P < 0.05$).

†Significant deviations from chance, calculated by two-tailed t-test ($P < 0.01$).

temporal filtering and rectification in recovering the modulation. We can see from Fig. 4 that image processing operations that are effective in recovering forward motion in luminance modulations are just as effective in the case of modulations of the block noise carrier. Thus, one cannot explain the substantial differences found in motion detection in relation to processing within the second-order channel. To sustain the two-channel model one must argue that this difference results from interaction between information processed by separate channels. For example, the detrimental effect of the block noise carrier might be explained by proposing that the first-order characteristics of the carrier affect the perception of second-order motion by creating "motion noise" in the first-order channel. This could affect the percept of second-order motion at an integration stage.

The experiment described above was carried out to replicate the data obtained in a slightly different experiment. In this experiment subjects viewed stimuli from 2 and 6 m. At the 2 m distance the patterns had spatial frequencies of either 1.92 or 0.96 c/deg. Apart from the use of an oval window, the procedure and luminance values used were identical to those of the present experiment. From a viewing distance of 1 m this window had the same maximum vertical and horizontal extents as the rectangular window used in Experiment 1. Again eight subjects took part in the experiment, four of which subsequently took part in the Experiment 1. Results for the "oval window" experiment are shown in Fig. 7 and in Table 2. The results from the two experiments are very similar.

Experiment 2: carrier type

In the previous experiment reversed motion in Γ_C stimuli with dynamic 1D carriers was not seen. Forward motion was perceived in Φ_C stimuli. One possible explanation for this difference is that the threshold for detection of motion direction in Γ_C stimuli is higher than that for Φ_C stimuli. If this is the case then the use of a different binary noise carrier may bring the direction of motion in the Γ_C stimulus above threshold.

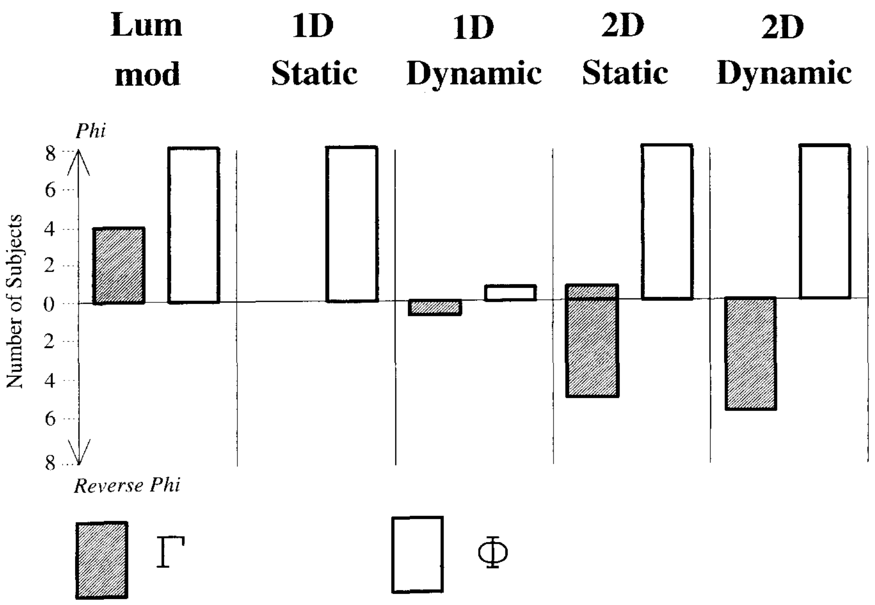

FIGURE 8. Numbers of subjects perceiving forward and reversed motion in luminance-defined and contrast-defined Γ and Φ stimuli. Bar charts identified by a noise type (i.e., 1D static) show results for contrast-defined stimuli.

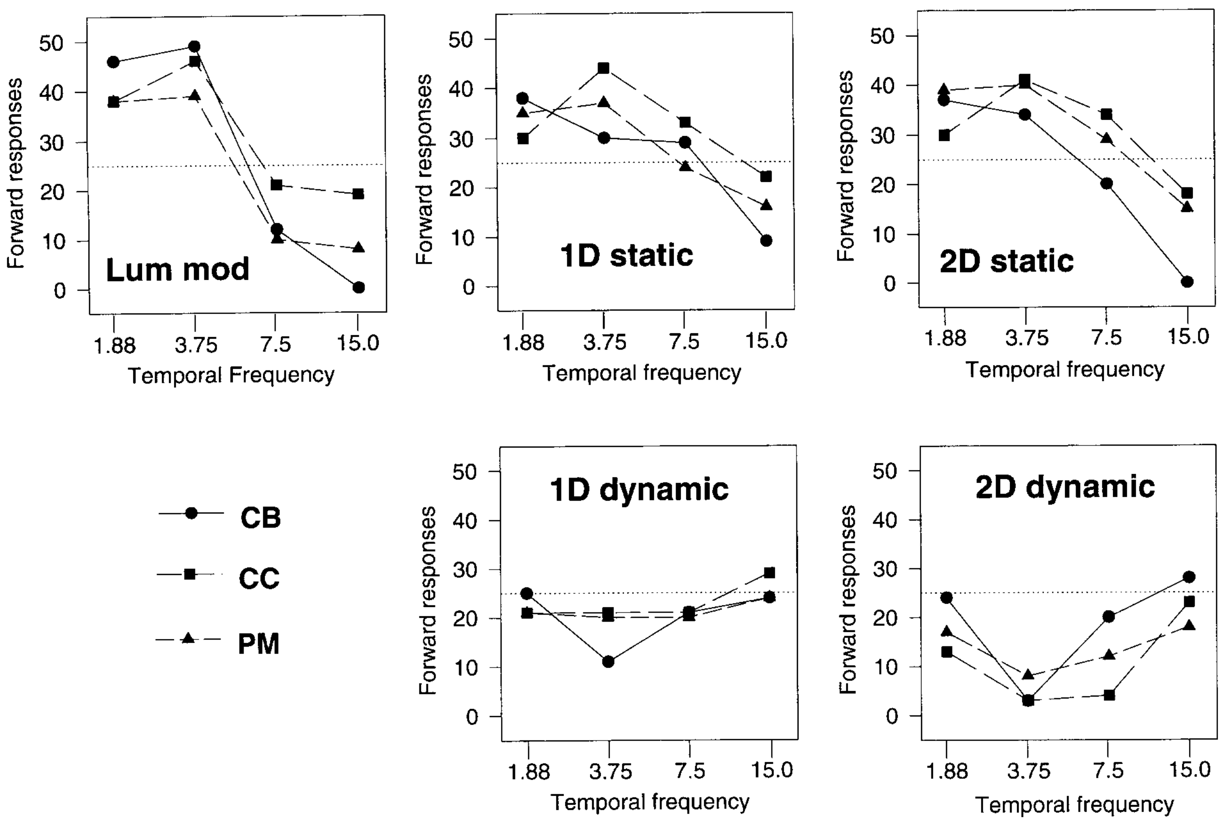

FIGURE 9. Number of forward responses over modulant temporal frequency for Γ_L and Γ_C stimuli. Graphs identified by noise type indicate results for contrast-defined stimuli with that particular carrier. Points above the dotted lines show a bias in number of responses towards forward motion, points below show a bias towards reversed motion.

Eight subjects were tested with Φ_C and Γ_C stimuli over four different binary noise carriers: 1D static noise, 1D dynamic noise, 2D static noise and 2D dynamic noise. Figure 3 shows sample frames from typical motion sequences to illustrate these stimuli. Luminance-defined Φ_L and Γ_L stimuli were also tested. The spatial and temporal frequencies of the modulants in both the luminance- and contrast-defined stimuli were 0.83 c/deg and 3.75 Hz. The width of the noise used in the carrier for the contrast-defined stimuli was 3.94 arc min. The temporal duration of the dynamic noise elements was 17 msec. Subjects viewed the stimuli from 1 m. Unless otherwise specified, the spatial and temporal extents of the noise and the viewing distance should be assumed to take these values for all subsequent experiments described in this study. Subjects were presented with 30 trials for each of the 10 stimulus types. The data for all of these were collected in a single session. The stimuli were randomly interleaved; data collection and within-subjects analysis were identical to that described for Experiment 1.

Figure 8 shows results in terms of numbers of subjects reporting a coherent direction of motion. In agreement with Nishida (1993), reversed motion is perceived with 2D noise carriers. With Φ_C stimuli, forward motion is readily perceived except for 1D dynamic noise carriers. The threshold hypothesis is clearly supported by these data. The perception of reversed motion in Γ_C stimuli seems particularly sensitive to the dimensionality of the noise with no evidence for any coherent direction of perceived motion for 1D carriers. The results suggest the following ordering in direction discrimination performance for the various noise carriers:

1D dynamic <1D static <2D static <2D dynamic.

In the previous experiment, observers clearly saw motion in Φ_C stimuli with a 1D dynamic carrier; however, in the present study there was no reliable perception of motion in this case. The most reasonable explanation for this difference is that in this experiment the noise was nearly four times wider than that used in Experiment 1 (3.94 min compared with 0.98 min).

It is clear that the type of carrier can have a profound effect on the direction of perceived motion. Effects of carrier on the perception of second-order motion have been noted before (Johnston & Clifford, 1995b) and it would also appear that the nature of the carrier can affect the motion aftereffect for second-order stimuli (Cropper & Hammett, 1996). Additionally, in the spatial domain the orientation of the carrier can affect the perceived orientation of the envelope (McOwan & Johnston, 1996a). One cannot explain differences in motion perception due to the nature of the carrier simply on the basis of the presence or absence of a pointwise nonlinearity. The dimensionality of a carrier will have no influence on the rectified signal. One can see in Fig. 4(b) that the temporal filtering plus rectification approach advocated by Chubb and Sperling can readily recover the

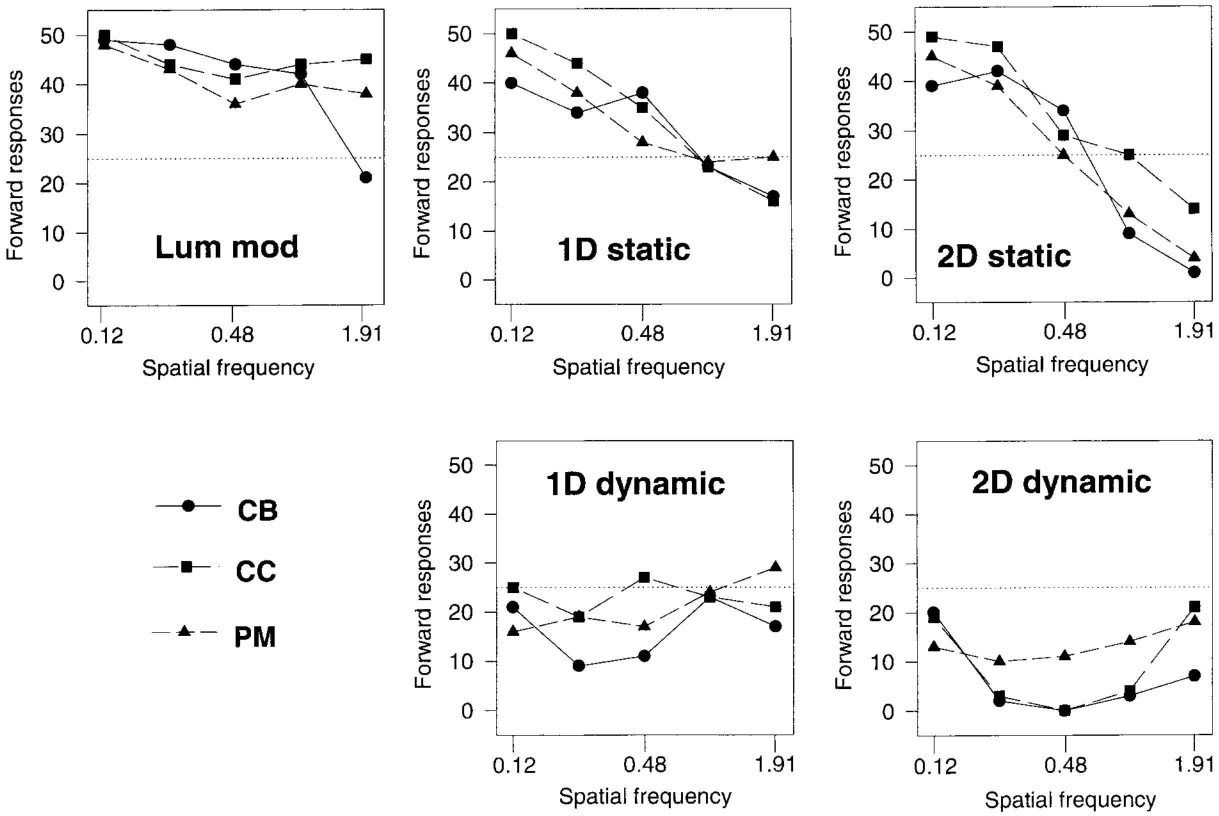

FIGURE 10. Number of forward responses over modulant spatial frequency for Γ_L and Γ_C stimuli. Graphs identified by noise type indicate results for contrast-defined stimuli with that particular carrier.

modulation in the case of 1D dynamic carriers. Since the space–time image in Fig. 4(b) simply represents one slice through a space–time volume, it is clear that the results of applying the Chubb and Sperling strategy would be the same for 1D and 2D carriers. Any differences in perception need to be explained in terms of the match between the carrier and the initial filters in the putative second-order channel. However, it is difficult to see why filters in the second-order channel should be more sensitive to 2D spatial carriers than to 1D spatial carriers.

Experiment 3: modulant temporal frequency

In Experiment 2 we showed that carrier type can have a profound effect on the perception of reversed motion in Γ_C stimuli. Sperling & Lu (1996) showed that, at low temporal frequencies, forward motion could be observed in Γ_C motion sequences. In this experiment we expanded on this work by looking at the effect of carrier type on the perception of motion in Γ_C stimuli over a range of modulant temporal frequencies. We additionally examined the effect of temporal frequency on the Γ_L stimulus. We used the same four binary noise carrier types as used in Experiment 2. Spatial frequency was fixed at 0.24 c/deg and four levels of temporal frequency were employed: 15, 7.5, 3.75 and 1.88 Hz.

Subjects made 50 responses to each level of each stimulus type. We recorded the number of responses indicating perceived motion in the forward direction. A score of 50 means that the subject responded in the forward direction on every presentation, whilst a score of 0 means that the subject responded solely in the reversed direction. Three subjects, all experienced psychophysical observers, took part in this experiment; two of the authors (CB and PM), and one naïve subject (CC). Figure 9 shows responses to Γ_L and Γ_C stimuli over a range of temporal frequencies for all three subjects.

Luminance-defined stimuli. All subjects showed a strong reversal. Forward motion was dominant at low temporal frequencies, and reversed motion was dominant at high temporal frequencies. Reversal occurred at about 6 Hz.

Static vs dynamic carriers. With a static carrier a strong reversal was seen, with forward motion dominant at low temporal frequencies. This reversal appeared to occur at about 7.5 Hz. With a dynamic carrier there was no strong evidence for any percept of forward motion. The percept of reversed motion appears to peak at about 3.75 Hz and at this frequency there is a strong difference between the perceived direction of motion for the static and dynamic carriers.

1D vs 2D carriers. Results with 1D carriers appear to be similar to those obtained with 2D carriers, but with responses in the former being a muted version of those in the latter.

The results of Sperling & Lu (1996) are supported, at least in the case of a 2D static carrier. The change from perception of forward motion at low temporal frequencies to reversed motion at high temporal frequencies

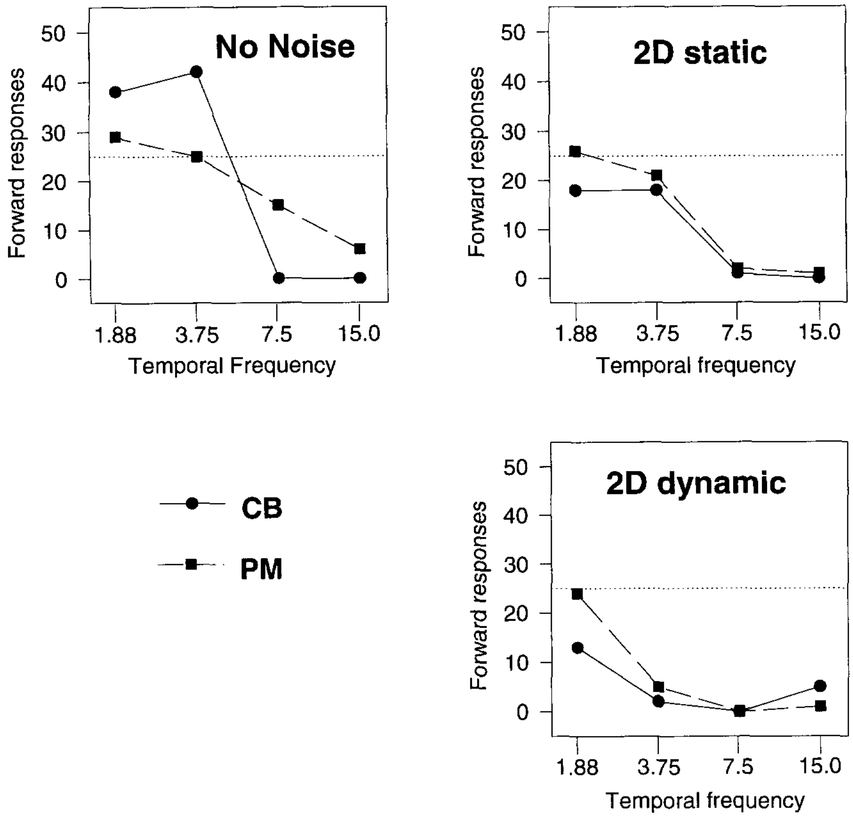

FIGURE 11. Number of forward responses over temporal frequency for Γ_L stimuli with additive noise.

appears to occur at 7.5 Hz, as was also shown by Sperling and Lu. The use of 1D dynamic noise appears to inhibit any strong motion percept which agrees with our findings in the previous two experiments. In the present experiment we find a very pronounced effect of carrier type on the perception of motion direction in contrast-defined stimuli. Indeed at 3.75 Hz subjects see motion in the forward direction with a static 2D carrier, and motion in the reversed direction with a dynamic 2D carrier.

Experiment 4: modulant spatial frequency

In Experiment 3 we showed that a reversal is found over temporal frequency in both luminance and contrast-defined Γ stimuli. With Γ_L stimuli, a reversal is also found with increases in viewing distance (Chubb & Sperling, 1989a; see also Experiment 1). In this experiment we address the question of whether a similar shift in perceived direction may occur in Γ_C stimuli with a reduction in modulant spatial frequency. This experiment is identical to the previous one, except that temporal frequency was fixed at 3.75 Hz and spatial frequency took the following values: 0.12, 0.24, 0.48, 0.95 and 1.91 c/deg. Figure 10 shows responses to Γ_L and Γ_C motion sequences over spatial frequency for all three subjects.

Luminance-defined stimuli. There appears to be little effect of spatial frequency. Subjects consistently reported forward motion. Initially, this appears to be at odds with the findings of Chubb & Sperling (1989a) who did obtain reversed motion with this stimulus at long viewing distances. However, the spatial frequency of their stimulus at the far viewing distance (8 m) was 12.5 c/deg, an order of magnitude greater than the maximum used in the present experiment.

Static vs dynamic carriers. In modulations of static carriers there is a reversal of perceived motion direction with increasing spatial frequency. Reversed motion is found at the higher spatial frequencies. The reversal appears to occur at about 0.5 c/deg. This is directly analogous to the results reported with the luminance-defined stimulus by Chubb & Sperling (1989a) except that the reversal occurs at a far lower spatial frequency. With dynamic carriers the percept of forward motion seems to be completely abolished, at least over the range tested in this experiment. Choice of carrier can, therefore, completely change the perceived direction of motion of this stimulus.

1D vs 2D carriers. Results with 1D carriers appear to be similar to those obtained with 2D carriers except that the percepts of both forward and reversed motion appear to be strongly inhibited in the case of the former.

It appears that, at least in the case of a 2D static carrier, a reversal of motion direction can be obtained with Γ_C stimuli. In the temporal domain the point at which the reversal occurs is similar for both Γ_L and Γ_C stimuli (see Experiment 3). In the spatial domain, the reversal point is an order of magnitude greater (in terms of spatial frequency) for luminance-defined stimuli than for contrast-defined stimuli. It would seem, therefore, that we have a clear quantitative difference between luminance-

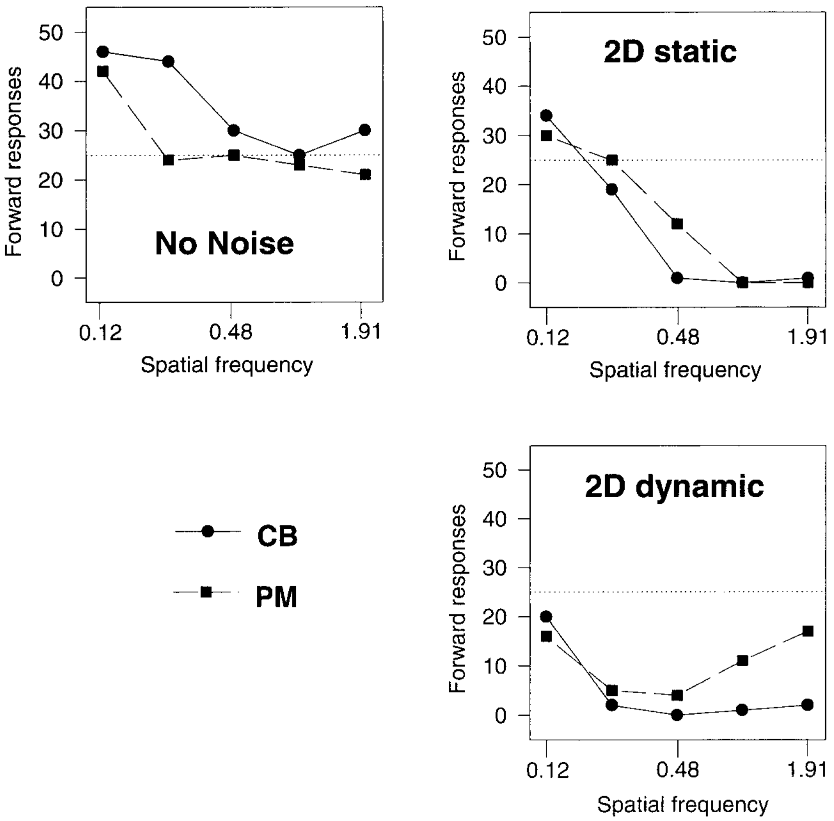

FIGURE 12. Number of forward responses over spatial frequency for Γ_L stimuli with additive noise.

and contrast-defined stimuli, with the latter giving rise to changes at a coarser spatial scale. It is certain from these experiments that the nature of the binary noise carrier can have a considerable effect on the perceived direction of motion of the contrast-defined stimulus.

It is possible that the characteristics of the carrier are the critical determinants of the perception of motion direction in these tasks, rather than qualitative differences in the processing of first- and second-order stimuli. If this is the case then a single mechanism might show similar dependence on noise whether it is multiplicative, as in the case of contrast-defined motion patterns, or additive. Although one cannot reproduce a contrast-defined signal by adding noise to a luminance modulation, we can nevertheless attempt to examine the effects of the characteristics of the noise used in the contrast-defined stimuli by adding similar noise patterns to luminance-defined stimuli. If one finds that the addition of noise produces a similar pattern of results to that seen in second-order motion sequences, one may reasonably conclude that the nature of the noise determines the pattern of response rather than the architecture of the motion system.

Experiment 5: additive noise and temporal frequency

In this experiment we examined the effects of additive binary noise on the perception of direction of motion in Γ_L stimuli. As the strongest effects in the contrast-defined stimuli (see Experiments 3 and 4) are seen with the 2D carriers, we used only 2D additive noise. In order to allow enough luminance range for the addition of noise, the contrast of the Γ_L stimulus was reduced to 0.19. In Experiment 3 the contrast of the Γ_L stimulus was 0.88. Binary noise (± 9.73 cd/m^2) was added to the stimulus. The spatial and temporal parameters of the noise were identical to those used in Experiments 2–4. Modulant spatial frequency was fixed at 0.24 c/deg and temporal frequency took the following four values: 15, 7.5, 3.75 and 1.88 Hz. Figure 11 shows the results as a function of temporal frequency for both subjects.

It would appear that the addition of noise also leads to a reversal of perceived motion direction in Γ_L motion patterns. In subject CB, at 3.75 Hz motion was seen in the forward direction with the unadulterated stimulus and in the reversed direction with the addition of 2D dynamic noise. There is no substantial difference between the responses to the luminance-defined stimuli presented without added noise found here and those found in Experiment 3, despite the difference in contrast. The pattern of results for additive noise was very similar to that found with multiplicative noise. In particular, the forward motion elicited by the Γ_L stimulus is eliminated for additive 2D dynamic noise, as was the case for modulation of 2D dynamic noise in Experiment 3. A similar patterns of results was seen for static noise, although the reduction in the probability of seeing forward motion was less profound.

Experiment 6: additive noise and spatial frequency

Here we extend the results of the previous experiment

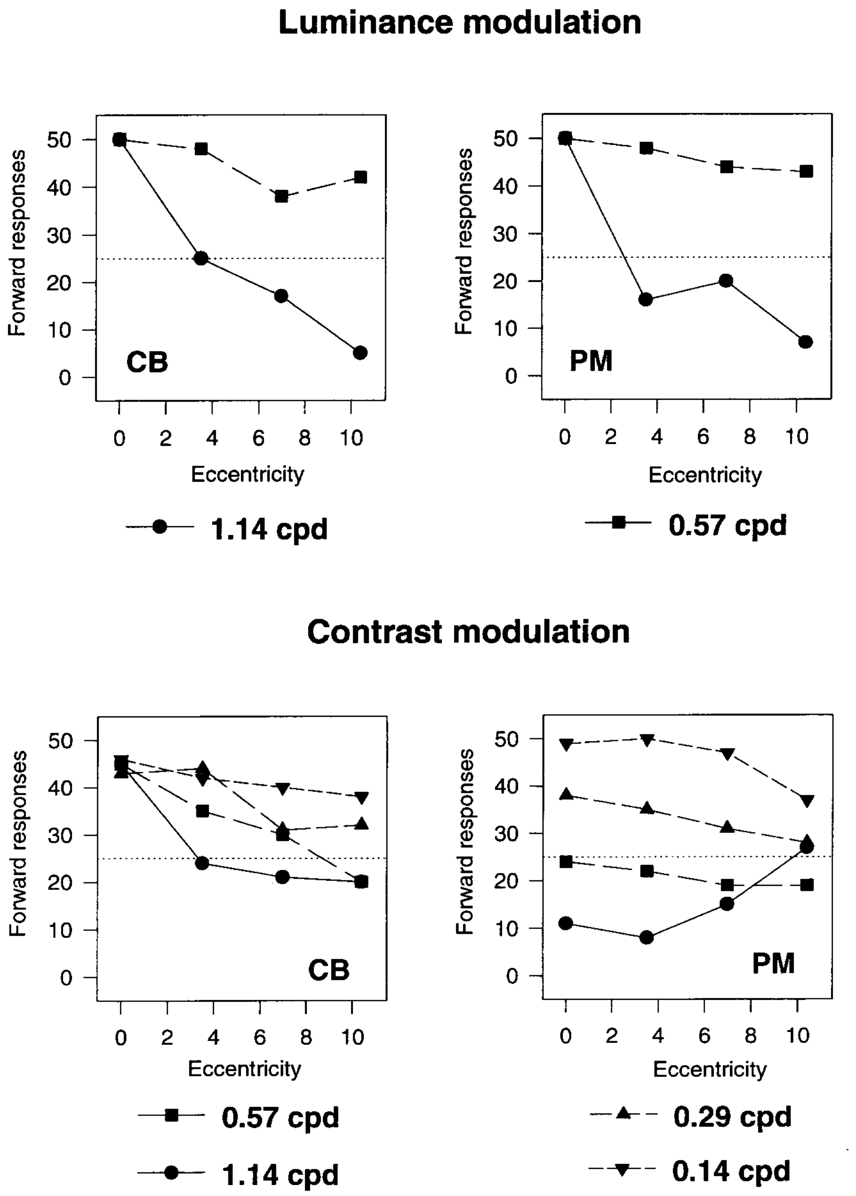

FIGURE 13. Number of forward responses over eccentricity for Γ_L and Γ_C stimuli. Eccentricity is measured in degrees of visual angle.

by examining the effects of adding static and dynamic 2D noise to Γ_L stimuli as a function of spatial frequency. Temporal frequency was fixed at 3.75 Hz and spatial frequencies of 0.12, 0.24, 0.48, 0.95 and 1.91 c/deg were tested. The contrast of the stimuli and amplitude of the additive noise were identical to those used in the previous experiment. Data are shown in Fig. 12.

This experiment confirms the observation made in Experiment 5 that additive noise can reverse the perceived direction of motion in Γ_L stimuli. Whereas in Experiment 4 there was no effect of the spatial frequency of the luminance modulation on perceived direction of motion, here we find a strong reduction of forward motion at the higher spatial frequencies in the unadulterated stimulus. Thus, there appears to be a strong effect of contrast on perceived direction of motion in stimuli of this type. The differences between additive 2D static and dynamic noise, outlined in Experiment 5, are far more clearly delineated here. The pattern of results for additive noise was very similar to that found with multiplicative noise for both dynamic and static noise, although there is a weaker tendency to see forward motion overall. In other words, it appears that both dynamic and static noise inhibit the perception of forward motion in this stimulus, but dynamic noise does so to a greater extent. In Experiments 5 and 6 the addition of noise gave rise to a similar pattern of results to that found for multiplicative noise in Experiments 3 and 4.

Experiment 7: eccentricity

Sperling & Lu (1996) examined the effect of eccentricity on Γ_C stimuli and found that subjects did not report forward motion for stimuli viewed peripherally (5 deg). In this experiment we investigated the effect of

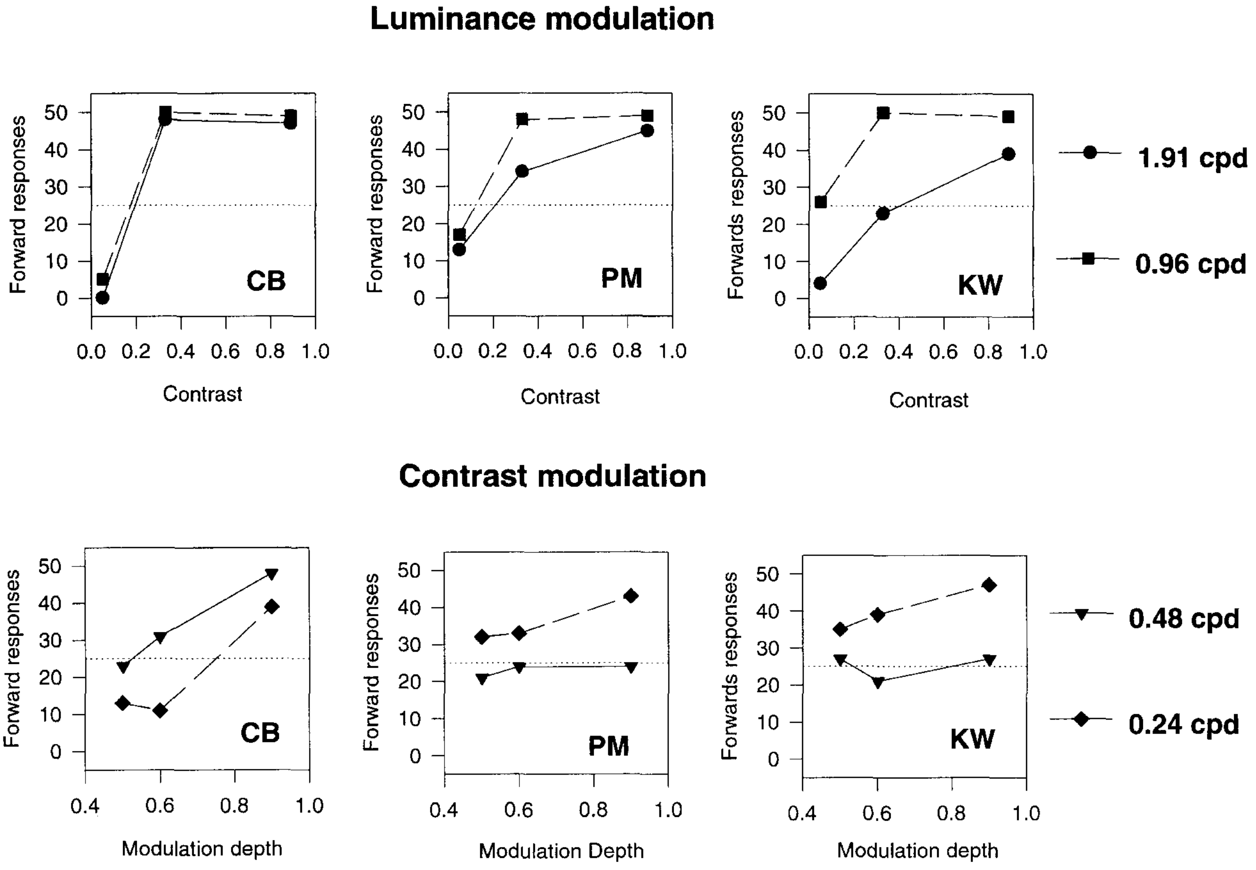

FIGURE 14. Number of forward responses over contrast for Γ_L stimuli and over modulation depth for Γ_C stimuli.

eccentricity on Γ_C motion sequences with a static 2D carrier at a number of different envelope spatial frequencies. The effect of eccentricity on Γ_L stimuli was also examined.

For this experiment we chose a viewing distance of 60 cm. The rectangle within which the stimuli were displayed had a height of 20.75 deg and a width of 13.96 deg. This window was split into two equal halves from top to bottom; each half was displaced laterally by an equal distance from a central fixation point. The eccentricity was a measure of the distance from the fixation point to the inside edge of each of the two images. When eccentricity is zero, there is therefore, one image in the centre of the screen. When this was the case the fixation spot was overlaid by the stimulus; it was present at all other times. The width of the noise in this experiment was 6.56 minutes. Figure 13 shows the results from this experiment and the spatial frequencies over which subjects were tested. The temporal frequency of the stimuli was fixed at 3.75 Hz.

In the luminance-defined stimulus there was a strong effect of eccentricity, with forward motion perceived in the fovea and reversed motion in the near periphery. This effect is strongly dependent upon spatial frequency. With the contrast-defined stimulus there appears to be no such effect. With increasing eccentricity, it appears to be more difficult to see motion in either direction.

Smith *et al.* (1994) showed that detection and direction thresholds for first- and second-order stimuli increase at similar rates as eccentricity increases. Their data also suggest that the modulation depth sensitivity curve across spatial frequency shifts downwards as eccentricity is increased, an effect that parallels the change in contrast sensitivity with visual eccentricity (Rovamo & Virsu, 1979; Johnston, 1986, 1987; Drasdo, 1991). Since there is an increase in the spatial grain of visual analysis from fovea to periphery, increasing eccentricity and increasing spatial frequency at a particular locus in the visual field should have similar effects on motion perception. Given that we found a strong effect of spatial frequency on the perceived direction of motion in contrast-defined stimuli, one might also expect a reversal of perceived motion direction with increasing eccentricity. Furthermore, a reversal of direction with this stimulus over eccentricity has been reported by Sperling & Lu (1996). At present, we can find no convincing explanation for the lack of such a finding in this study.

Experiment 8: modulation depth

In Experiment 6 we noted that the percept of forward motion was weaker in low contrast Γ_L stimuli than in high contrast Γ_L stimuli. In this experiment we examined the effect of contrast on Γ_L motion sequences, and modulation depth on Γ_C stimuli with a 2D static carrier. For the luminance-defined stimuli, contrasts of 0.05, 0.33 and 0.89 were used. For the contrast-defined stimuli the modulation depths were 0.5, 0.6 and 0.9. Figure 14 shows the results for this manipulation and lists the spatial frequencies of the stimuli. Temporal frequency was held at 3.75 Hz.

For the Γ_L stimulus, there is a very strong effect of contrast, with reversed motion perceived at low contrasts and forward motion perceived at high contrasts. Since reversed motion is seen at low contrasts, it is possible that this is an effect of internal noise. If so, it would be analogous to the effects of additive noise found in Experiments 5 and 6. In the case of the Γ_C stimulus there is a tendency for the perception of forward motion to decline with decreases in modulation depth, but this is not as pronounced as that found with a reduction in contrast of the luminance-defined stimulus.

DISCUSSION

Chubb & Sperling (1989a) designed a luminance-defined motion sequence, Γ_L, which appears to move forward at close viewing distances but in the opposite direction at greater viewing distances. We have shown that this reversal can also be generated by increasing spatial frequency, increasing temporal frequency, reducing contrast, adding binary noise and increasing eccentricity. Chubb and Sperling argued that the reversal of apparent motion is evidence for two separate motion systems. They proposed that, in addition to a linear motion energy channel, there exists a second-order or non-Fourier channel which includes a fullwave rectification stage prior to motion analysis. This mechanism is used to explain the percept of forward motion in the Γ_L stimulus whilst reversed motion is explained in terms of the linear channel.

Motion reversal can also be elicited by a contrast-defined version of the original Chubb & Sperling (1989a) stimulus, Γ_C. Reversed motion is seen at high spatial frequencies and high temporal frequencies. The forward motion seen at low spatial and temporal frequencies in this stimulus cannot be accounted for within the two-channel framework offered by Chubb & Sperling (1989a). As the stimulus is a contrast modulation of binary noise, it should elicit no consistent response in the first-order channel; however, the filtering and rectification stages in the second-order channel should recover the modulant, or a distorted version of it. As all the motion energy in the recovered modulant will be in the reversed direction, standard motion energy analysis in the second-order channel should signal motion only in the reversed direction.

Chubb & Sperling (1989a) explained the forward motion in the luminance-defined stimulus by proposing a second-order motion mechanism. In a similar vein, Sperling & Lu (1996) proposed an additional "third-order" motion mechanism to account for forward motion seen in the contrast-defined stimulus. Their definition of "third-order" motion appears to refer to any motion that cannot be detected by their first- and second-order mechanisms. Within the framework of their tripartite architecture of human vision (Lu & Sperling, 1995b), third-order motion is detected by a third-order feature tracking mechanism.

It is often thought that if some motion pattern is not visible to a specific computational mechanism, then another mechanism must exist to account for the perception of that motion. Of course, another approach is also possible. The fact that we can see non-Fourier motion may mean that we have to adjust the existing computational models of low level motion perception rather than add additional mechanisms. In this framework, the percept of non-Fourier motion might be described as epiphenomenal rather than the product of some special system designed to analyse second-order motion. An example of a model in which the perception of second-order motion is emergent is provided by the Multi-Channel Gradient Model (MCGM) described by Johnston *et al.* (1992) and more recently by McOwan & Johnston (1995). Although not designed to recover second-order motion *per se*, this model does successfully describe the perception of motion in contrast modulated sinewave gratings (Johnston & Clifford, 1995b) and can also account for the dependence of perceived motion direction on spatial frequency with the luminance-defined Γ_L stimulus (Johnston & Clifford, 1995a). When extended into the motion domain, the spatial primitives approach developed by Watt & Morgan (1985) can also account for this reversal of perceived motion direction over spatial frequency without recourse to an additional mechanism (Morgan, personal communication).

The purpose of the postulated second-order channel is to extract the modulant in second-order motion sequences. A basic design criterion of any envelope detection device must be the minimization of any influence of the carrier upon the extraction of envelope motion. The second-order channel is seen as having an initial spatio-temporal filtering stage that precedes the nonlinearity. The match between the carrier and these linear filters will determine the subsequent signal strength. It is, therefore, easy to see how the frequency characteristics of the carrier can affect the amplitude of the recovered modulant. However, the perceived direction of motion in Γ_C patterns shows a profound dependence upon carrier type. Indeed, the choice of carrier can affect the perception of motion in this stimulus to such a degree that forward motion may be seen with a 2D static carrier, whilst only reversed motion is elicited with a 2D dynamic carrier. It is difficult to see how these carrier effects can readily be explained within the context of a second-order channel.

When comparing responses for contrast-defined Γ_C stimuli over temporal and spatial frequency, results with 1D carriers appear to be similar to those obtained with 2D carriers, but with responses to the former being a muted version of those to the latter. With 1D carriers, all of the noise has the same spatial orientation as the motion signal. We might, therefore, expect that 1D carriers should interfere with or mask the motion signal to a greater degree than 2D carriers. If this is correct, then we should find a similar decrement in performance in luminance-defined signals with 1D additive noise compared with those with 2D additive noise. At present, we are not aware of any such evidence within the motion domain. However, a study by Rovamo & Kukkonen (1996), examining the detection of static sinewave gratings, showed that detection was more difficult with 1D additive noise than with 2D additive noise.

It is clear that the extraction of envelope motion can be radically affected by the nature of the carrier. Such an idea is inimical to models based on demodulative processes, where the whole idea of the proposed mechanism is to extract the modulant whilst effectively discarding the carrier. Such models would predict separability between carrier and envelope processing. This prediction is not supported by our results. It has been proposed that the computation of velocity may be best understood with reference to the local geometry of the spatio-temporal luminance surface rather than the Fourier composition of the motion pattern (Johnston *et al.*, 1992). In the case of a contrast modulation, the local geometry is determined by the properties of both the carrier and the modulant. Of course the form of the carrier will always affect the local surface geometry and therefore the performance of models based upon local geometry will always be susceptible to carrier effects. Indeed, studies that examine "carrier-modulant" separability can potentially discriminate between these two theoretical approaches. For example, Cropper & Badcock (1995) showed that the perceived direction of motion in contrast-defined plaids was critically dependent upon the orientation bandwidth of the carrier.

We found that the addition of noise to luminance-modulated sequences could radically affect perceived direction of motion. The perceived direction of motion in Γ_C sequences changed as one increased the spatial frequency of the modulant. The spatial frequency at which forward motion began to perceptually dominate was estimated to be an order of magnitude greater for high contrast Γ_L sequences than that for Γ_C sequences. However, this difference between luminance-modulated and contrast-modulated stimuli was eradicated by reducing the contrast of the Γ_L stimulus and then adding noise. This suggests that some of the effects in the second-order motion literature which have been attributed to the properties of first- and second-order channels may in fact be more parsimoniously explained as due to problems in the recovery of coherent signals from noise (McOwan & Johnston, 1996b). The perception of motion in the luminance- and contrast-defined stimuli appears to follow a similar pattern of response with respect to changes in modulant temporal and spatial frequency. Indeed, the data for contrast-defined patterns appear to be similar to those found with noisy low contrast luminance-defined patterns. This at least suggests the possibility that a single mechanism may mediate the perception of both forward and reversed motion, in both the luminance- and contrast-defined stimuli.

In summary, we examined the perception of motion direction in luminance- and contrast-defined Γ stimuli. We found that both forward and reversed motion could be elicited by both Γ_L and Γ_C stimuli. The forward motion in the latter cannot be explained by traditional two-channel models. An additional mechanism is needed to account for the forward motion, necessitating a tripartite architecture. However, it is not clear how the profound carrier dependencies detailed in this study could be explained by such an approach. An alternative analysis is offered, in which motion perception in both luminance- and contrast-defined stimuli is mediated by a single, as yet undetermined, mechanism which shows a similar sensitivity to noise, whether that noise is additive or multiplicative.

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