



# Failure of signed chromatic apparent motion with luminance masking

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## Abstract

It has been suggested that there are two types of chromatic motion mechanisms: signed chromatic motion, in which correspondence across successive frames is based on chromatic content of image regions, and unsigned chromatic motion based on movement of chromatically-defined borders. We investigate whether signed and unsigned red–green chromatic motion are mediated by a genuinely chromatic mechanism. Direction discrimination of signed and unsigned red–green chromatic motion were measured in the presence of a dynamic luminance masking noise. Increasing the luminance noise contrast systematically impaired signed motion, regardless of contrast and speed. This result suggests that signed red–green chromatic motion is derived from a luminance-based signal, rather than a genuinely chromatic motion mechanism. In the case of unsigned chromatic motion, there is no effect of luminance masking noise, indicating there exists a genuine chromatic mechanism for second-order motion perception.

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## 1. Introduction

A powerful analytical approach to studying motion perception has been apparent motion, since it affords the opportunity to manipulate separably the spatial and temporal parameters of movement as well as dissection of how motion mechanisms establish correspondence of image attributes in successive frames. In principle there are two kinds of chromatic apparent motion to consider, termed “signed” and “unsigned” (Dobkins & Albright, 1993; see also, Morgan & Ingle, 1994; Papatomas, Gorea, & Julesz, 1991), and these are best illustrated in space–time diagrams of multi-frame chromatic apparent motion (Fig. 1). In signed chromatic motion (solid lines in Fig. 1), correspondence across successive frames is established by matching image regions with the same color. Because such motion could be mediated by a simple linear spatio-temporal filtering mechanism driven by chromatically labeled inputs, it has been considered first-order by some authors (Cavanagh & Mather, 1989; Chubb & Sperling, 1988). Alternatively, such signed chromatic apparent motion might be mediated by luminance signals, for example those generated

by temporally dynamic chromatic stimuli (Stromeyer, Kronauer, Ryu, Chaparro, & Eskew, 1995).

For unsigned chromatic motion (dashed lines in Fig. 1), correspondence is established on the basis of transitions in chromaticity regardless of the constituent colors defining them, hence chromatic information per se is not used. A mechanism encoding such motion would necessarily entail a nonlinear operation on its inputs, and thus would be considered second-order (Baker, 1999; Baker & Mareschal, 2001).

Evidence for both signed and unsigned chromatic motion has been reported for human vision (Cropper & Derrington, 1996; Dobkins & Albright, 1993), although these results conflict with a previous earlier report that apparent motion fails for isoluminant stimuli (Ramachandran & Gregory, 1978). The reports of chromatic signed and unsigned motion raise two key questions, which we address here. Firstly, there is now mounting evidence to show the intrusion of luminance signals into the motion of red–green isoluminant stimuli. These signals are physiological in origin and probably arise at a retinal level from temporal delays in the L and M cone inputs to a luminance channel, with the net result of inducing a luminance response from a chromatically modulated moving or flickering stimulus (Stromeyer, Chaparro, Tolia, & Kronauer, 1997; Stromeyer et al., 1995; Stromeyer et al., 2000; Swanson, 1994; Tsujimura,

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Shioiri, Hirai, & Yaguchi, 1999, 2000). The question arises as to whether these artifactual luminance signals have influenced the measurements of signed or unsigned motion in color vision.

The second question relates to the division of signed and unsigned motion into linear and nonlinear motion processes, described above. Previous analyses of linear and nonlinear motion mechanisms using chromatic two-frame random Gabor micropattern kinematograms have suggested that the artifactual luminance contribution to chromatic motion is confined to linear motion mechanisms (Baker, Boulton, & Mullen, 1998; Yoshizawa, Mullen, & Baker, 2000a). These studies reported that the linear motion response (based on the Gabor carrier) could be eliminated by luminance noise masking, whereas the nonlinear response (based on the Gabor contrast envelope) was unaffected, indicating that the linear motion response is luminance based whereas the nonlinear one is genuinely chromatic. The fact that red–green chromatic noise selectively masks nonlinear but not linear motion provides strong additional support for this conclusion. These results allow a prediction to be made, that chromatic signed motion is affected by luminance artifacts but chromatic unsigned motion is not.

In this paper, we test these questions and clarify the nature of signed and unsigned chromatic apparent motion using isoluminant red–green stimuli presented in dynamic 1-d luminance noise masks. Stimuli are red–green gratings, either multi-frame (Dobkins & Albright, 1993, 1994) or very briefly presented in two-frame motion (Cropper & Derrington, 1996). We measure the effect of varying levels of luminance noise on motion identification of these moving stimuli under signed and unsigned motion conditions. Cropper and Derrington (1996) also used a luminance masker in an attempt to eliminate luminance artifacts, which was a static grating presented at a low fixed contrast (three times the detection threshold for the luminance stimulus). Here we have employed a potentially more powerful spatio-temporally dynamic luminance noise instead of a static luminance mask, and we systematically vary its contrast.

In the first experiment, we examine the effects of luminance noise masking on signed and unsigned chromatic motion of multi-frame presentations similar to those of Dobkins and Albright (1993, 1994). We find that regardless of the contrast and speed of the stimulus, signed chromatic motion is masked by luminance noise but unsigned chromatic motion is not. In the second experiment, we use a brief presentation of two-flash signed chromatic motion similar to that of Cropper and Derrington (1996) and measure the effect of luminance noise on motion performance for signed chromatic and luminance stimuli. We find that brief presentation signed chromatic motion is also masked by luminance noise. Our results suggest that signed red–green chro-

matic motion is mediated by a luminance-based signal and is not genuinely chromatic, consistent with our previous results reporting an absence of chromatic linear motion (Baker et al., 1998; Mullen, Yoshizawa, & Baker, submitted; Yoshizawa et al., 2000a).

## 2. Methods

### 2.1. Stimuli and apparatus

Stimuli were produced on a RGB monitor (Barco CCID 7751), driven by a PC-controlled graphics card (VSG2/2, Cambridge Research Systems) that uses an extended palette to supply 12 bits of luminance resolution. The monitor was refreshed with a frame rate of 150 Hz, noninterlaced. The spatial resolution of the screen was  $496 \times 428$  pixels, subtending  $21.5 \times 16.2^\circ$  at a viewing distance of 100 cm. The mean luminance of the stimulus was  $6.24 \text{ cd/m}^2$ . Details of calibration and gamma-correction are described in a previous paper (Yoshizawa et al., 2000a). For all stimuli, a small fixation point was displayed in the center of screen before the stimulus appeared and was extinguished at stimulus onset.

Stimuli were red–green sine-wave gratings displayed in apparent motion and were masked with luminance masking noise that was spatially 1-d and dynamic. These chromatic gratings were produced by summing red and green gratings (for details, see Baker et al., 1998). Chromatic contrast was defined conventionally, as the Michelson contrast of the component gratings. The red/green ratio was controlled by reciprocally varying the amplitudes of the component gratings, while keeping their Michelson contrasts equal. The test stimulus and noise mask were presented in alternate frames. Note that the frame-interleaving limits the maximum stimulus contrast to 50%. Contrast of the noise ( $C$ ) is defined by rms contrast  $C_{\text{rms}} = C/\sqrt{3}$ . Isoluminance was determined for each observer using a minimum motion technique and a continuously presented red–green Gabor stimulus. A mean of at least 20 minimum motion measurements was used for each observer.

### 2.2. Stimulus and procedure for experiment 1: signed and unsigned chromatic motion

The stimuli were similar to those of Dobkins and Albright (1993, 1994). A red–green isoluminant grating (0.45 cpd in a  $10 \times 10^\circ$  window) is presented in multi-frame apparent motion with a spatial displacement ( $\Delta$ ) of either  $90^\circ$  or  $12.9^\circ$  of phase. A space–time diagram of the stimulus is given in Fig. 1, which shows a horizontal profile of the spatial structure of the red–green grating illustrated as a function of time (running downwards). There are two possible cues for motion direction in such a stimulus as depicted in Fig. 1. “Signed” motion would

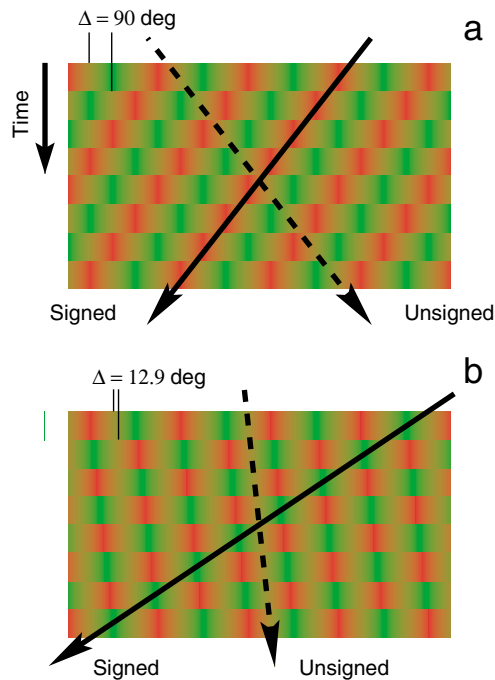


Fig. 1. Space–time diagrams of signed (—) and unsigned (---) multi-flash apparent motion of chromatic sine-wave gratings: (a) displacement  $\Delta$  is a quarter cycle of the grating, which typically produces a percept of motion in the signed direction and (b) displacement  $\Delta$  is smaller ( $12.9^\circ$ ), typically producing perceived motion in the unsigned direction.

result from a motion mechanism in which motion correspondence across displacements is based on color per se (solid lines). “Unsigned” motion, however, would emerge from a motion correspondence based on chromatic edges without regard for the sign of chromatic content on either side of the edge (dashed lines).

For the condition of an ambiguous phase displacement, the red–green grating shifts  $90^\circ$  every stimulus frame (Fig. 1a). Velocities of  $4.2$ ,  $8.3$  and  $13.9$   $\text{s}^{-1}$  were tested at durations of  $0.13$ ,  $0.27$  and  $0.53$  s. We tested stimulus contrast values of  $9.38\%$ ,  $18.8\%$  and  $37.5\%$ . For stimuli with phase shifts other than  $90^\circ$ , we refer to the speed or displacement in terms of the movement of the chromatic borders (unsigned direction). In experiments assessing unsigned chromatic motion, we use a phase shift of the unsigned chromatic border of  $12.9^\circ$ , corresponding to a velocity of  $1.2^\circ$   $\text{s}^{-1}$  (Fig. 1b, dashed arrow). (Note that the signed chromatic border moves at a phase displacement of  $167.1^\circ$  corresponding to  $15.5^\circ$   $\text{s}^{-1}$  in the opposite direction—Fig. 1b, solid arrow). We used stimulus durations of  $1.6$  (like Dobkins & Albright, 1993),  $0.53$ ,  $0.40$  and  $0.27$  s.

Direction discrimination performance was measured as a function of luminance noise contrast using a method of constant stimuli in which we varied the contrast of chromatic gratings. At least 80 trials per condition were tested on each observer.

### 2.3. Stimulus and procedure for Experiment 2

We used 1 cpd red–green and luminance sinusoidal moving gratings in this experiment in order to compare the results to those of Cropper and Derrington (1996). We, however, used a stimulus duration of  $53.3$  ms (frame exposures of  $26.7$  ms) instead of the  $16.7$  ms duration used by Cropper and Derrington (1996). For our experimental conditions, a duration less than  $53$  ms failed to produce reasonable levels of motion performance, even in the absence of a mask. Our duration of  $53.3$  ms is still short enough to avoid artifacts from rapid eye movements (Merrison & Carpenter, 1995), and our stimuli are otherwise comparable to those of Cropper and Derrington (1996). The stimulus and the luminance noise were presented in alternate frames at the video refresh rate of  $150$  Hz.

Detection thresholds and direction discrimination thresholds for motion were measured with a 2AFC procedure as a function of stimulus contrast. For the detection task, observers completed at least 5 runs with a staircase method. For the direction discrimination task, a method of constant stimuli was used with observers repeating at least 80 trials for each condition.

### 2.4. Observers

Two observers TY (experienced, author) and RPP (naive) participated, who had normal or corrected-to-normal acuity, and normal color vision as established by the Farnsworth–Munsell 100-Hue Test. Observers viewed the stimulus monocularly with natural pupils in a dimly lit room.

## 3. Results

### 3.1. Experiment 1: signed and unsigned chromatic motion

We employed different values of spatial displacement of the moving gratings to favor signed or unsigned motion selectively (Dobkins & Albright, 1993, 1994). A spatial displacement of a quarter cycle of the grating (Fig. 1a, “ambiguous phase displacement”) produced signed motion perception regardless of added luminance contrast, whereas when the spatial displacement ( $\Delta$ ) was relatively small (Fig. 1b), the direction of perceived motion corresponded to the direction of unsigned motion. In this experiment we investigate the effect of luminance noise masking on signed and unsigned motion performance. Luminance noise masking of the chromatic stimuli was employed to test for the contribution of luminance signals to the two types of motion of the chromatic stimuli.

Results for the ambiguous phase displacement ( $90^\circ$  phase shift) at a grating speed of  $4.2^\circ$   $\text{s}^{-1}$  are shown in

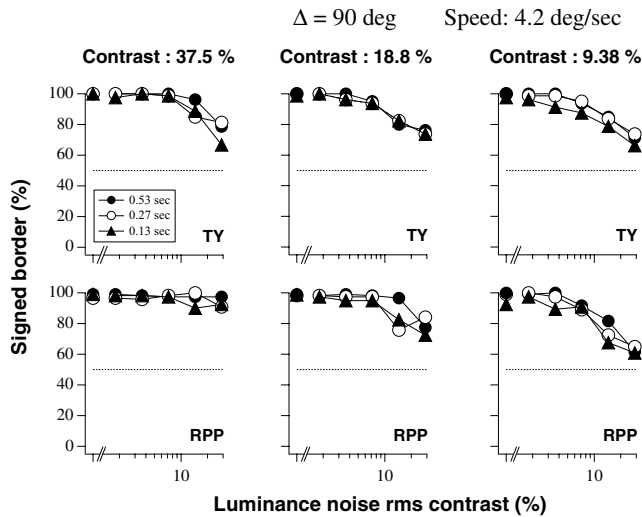


Fig. 2. Percent of trials in which observers report motion in the direction of signed motion, as a function of the luminance noise rms contrast for the stimulus shown in Fig. 1a (stimulus speed of  $4.2^\circ \text{ s}^{-1}$ ). Filled circles, open circles and filled triangles represent results for durations of 0.53, 0.27 and 0.13 s, respectively. Left, center and right panels are functions at the respective stimulus contrasts of 37.5%, 18.8% and 9.4%.

Fig. 2. Each plot shows the percentage of trials on which observers judged motion to be in the “signed” direction as a function of increasing luminance noise contrast; data are shown for durations of 0.53, 0.27 and 0.13 s (filled circles, open circles and filled triangles, respectively). First note that in the absence of a mask (leftmost point in each graph), values near 100% indicated observers consistently identified motion in the signed direction (solid arrow in Fig. 1), in agreement with Dobkins and Albright (1993). Increasing levels of luminance masking noise generally reduced the perception of motion in the signed direction; in both observers this effect was clearest at the lowest grating contrast tested (right graphs), and was progressively less evident for higher grating contrasts (middle, left graphs). These effects were essentially the same for all three stimulus durations tested.

Overall these results demonstrate that luminance noise progressively reduces signed chromatic motion in a way which trades off with chromatic contrast. The masking of this chromatic stimulus by luminance noise indicates that the motion percept is mediated by a luminance-based mechanism.

Since it has been suggested that chromatic motion is mediated by different mechanisms at different velocities (Hawken, Gegenfurtner, & Tang, 1994), we repeated the same experiments with a higher velocity of  $8.3^\circ \text{ s}^{-1}$  (Fig. 3). The results at  $8.3^\circ \text{ s}^{-1}$  are similar to those at  $4.2^\circ \text{ s}^{-1}$  (Fig. 2); increasing luminance noise reduces the perception of signed motion of the chromatic stimulus in inverse proportion to grating contrast and independently of stimulus duration. We also measured signed

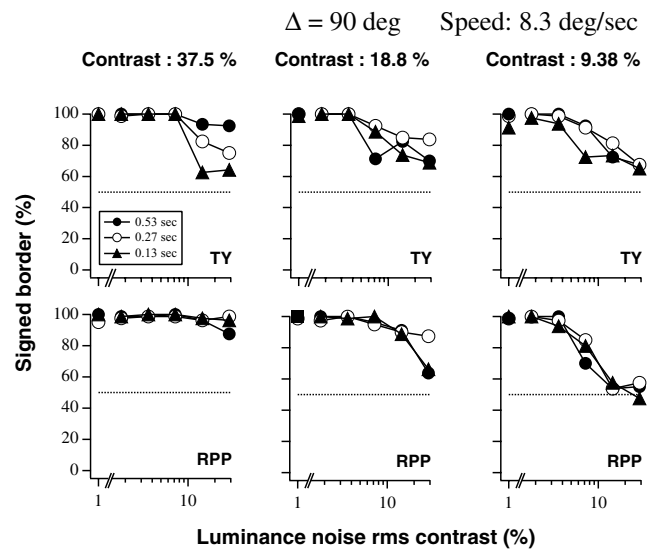


Fig. 3. Same as Fig. 2, but at a stimulus speed of  $8.3^\circ \text{ s}^{-1}$ .

motion perception at a higher velocity of  $13.9^\circ \text{ s}^{-1}$  for observer TY (data not shown). The results were similar to those obtained at the lower speeds; the functions drop as the luminance noise contrast increases and reach chance level at the maximum contrast of the noise.

To assess unsigned chromatic motion, we collected responses for a small spatial displacement of  $12.9^\circ$  as a function of the luminance noise contrast. The grating contrast was 37.5%. Results are shown in Fig. 4, plotted as the percentage of trials on which observers reported motion in the *unsigned* direction (Fig. 1b, dashed arrow). Filled circles, open circles, filled squares and open squares represent results for the durations of 1.6, 0.53, 0.4 and 0.27 s, respectively. In the absence of masking

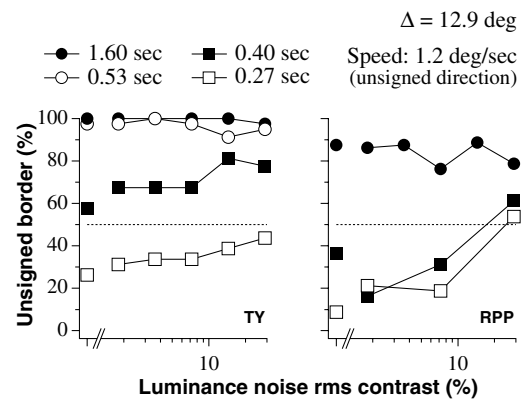


Fig. 4. Percent of trials in which observers report motion in the unsigned direction as a function of the luminance noise rms contrast, for the stimulus shown in Fig. 1b. Filled circles, open circles, filled squares, and open squares represent results for durations of 1.6, 0.53, 0.40, and 0.27 s, respectively. Results in the absence of luminance noise are given by the unconnected points beside the ordinate. Dashed lines indicate chance performance. The stimulus contrast was 37.5%.

noise (leftmost data points in each plot), clear unsigned direction motion was seen at the longer stimulus durations (1.60 and 0.53 s), in agreement with Dobkins and Albright (1993). At lower durations with no mask, unsigned motion detection was at chance levels (0.4 s) or was seen in the signed direction (0.27 s). In the presence of the luminance noise mask, the unsigned motion was maintained at all luminance noise contrasts of the mask. The signed motion (occurring at the shortest duration of 0.27 s), however, was reduced to chance levels as the masking luminance noise increased.

These results show that unsigned motion occurs only at longer durations of the stimulus, and is not affected by the luminance masking noise, indicating that it may be mediated by a truly chromatic mechanism. At shorter durations, motion is seen in the signed direction, and is affected by the luminance mask, indicating it is mediated by a luminance signal. The dependence of unsigned motion on long stimulus durations might reflect involvement of a secondary cue for motion identification, such as attentive position tracking. Alternatively, shorter durations might selectively impoverish a non-linear mechanism with slower temporal properties (see Section 4).

### 3.2. Experiment 2: brief presentation

Cropper and Derrington (1996) reported signed motion for chromatic grating stimuli with very brief presentation times. Short presentation times were selected to remove any possible influence of eye movements or attentive positional tracking. In experiment 2 we investigate the effect of luminance masking noise on signed motion for color and luminance stimuli under similar conditions and with brief presentation times (see Section 2). We used isoluminant and luminance grating stimuli of 50% contrast. We measured detection thresholds for these stimuli in each observer. For both observers (TY and RPP) the chromatic grating was about 1.0 log unit above their detection thresholds, while the luminance grating was about 1.47 (TY) or 1.41 (RPP) log units above detection. These ratios of stimulus contrast to detection thresholds are similar to those used by Cropper and Derrington (1996).

We measured percent correct direction discrimination of motion as a function of the luminance noise contrast using a method of constant stimuli. Fig. 5 shows percent correct for signed motion as a function of the masking luminance noise rms contrast. Filled and open symbols represent thresholds for chromatic and luminance stimuli, respectively. For both observers, performance for both chromatic and luminance stimuli decrease as the contrast of the luminance noise increases. At the maximum contrast of the luminance noise, performance for motion discrimination of both chromatic and luminance stimuli drops to near chance levels. These results

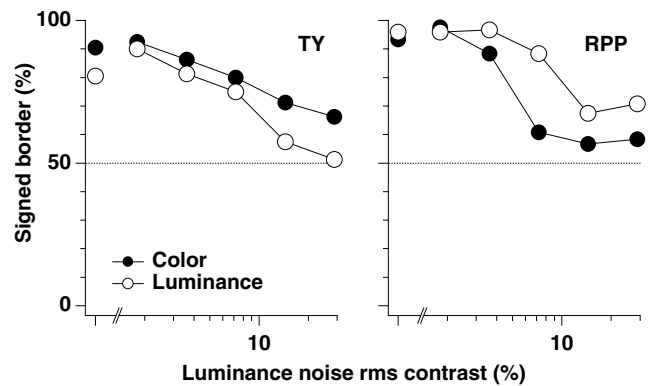


Fig. 5. Percent of trials in which observers report motion in the signed direction for very brief stimulus presentations, as a function of the luminance noise rms contrast. Filled and open symbols represent results for chromatic and luminance stimuli, respectively. Results in the absence of luminance noise are given by the unconnected points beside the ordinate.

indicate that motion processing for the chromatic stimuli, like that for the luminance stimuli, is mediated by a luminance sensitive mechanism. Even with these very brief stimulus presentations, for our observers signed chromatic motion is perceived only when a low contrast or no luminance noise mask is used.

## 4. Discussion

We have employed varying levels of luminance masking noise to assess the role of luminance signals generated by chromatic stimuli in signed versus unsigned motion, and to compare our results to previous results on linear versus nonlinear motion mechanisms. Our results in experiments 1 and 2 demonstrated that the signed motion of chromatic stimuli is masked by luminance noise, suggesting that the linear motion of chromatic stimuli is mediated by luminance-based mechanisms. The masking effects of luminance noise showed a reciprocity with stimulus chromatic contrast, consistent with mediation by luminance signals generated by the chromatic stimulus. These effects were robust with stimulus duration and velocity. On the other hand, we demonstrated (in Experiment 1) that unsigned chromatic motion is not affected by luminance noise, at least with the long presentations that we used.

These results are consistent with our previous work (Baker et al., 1998; Yoshizawa et al., 2000a) showing that linear chromatic apparent motion (measured with random Gabor kinematograms) is masked by luminance noise. These results suggest that the linear motion of chromatic stimuli is mediated by luminance mechanisms. In support of this conclusion, there are emerging reports that the motion of drifting chromatic gratings is masked by luminance noise (Mullen et al., submitted;

Stromeyer, Chaparro, & Kronauer, 1996; Yoshizawa, Mullen, & Baker, 2000b) and hence supported by luminance mechanisms. By contrast, we have shown that apparent motion based on nonlinear (second-order) motion mechanisms is unaffected by luminance noise, indicating that it is genuinely chromatic in nature with no intrusion from luminance signals (Baker et al., 1998; Yoshizawa et al., 2000a).

Since there are technical limits on the highest chromatic signal contrast that we can produce, it is conceivable that higher contrasts might recruit a signed chromatic motion signal that is impervious to luminance masking. However our attainable levels of chromatic contrast were sufficient to produce unsigned chromatic motion, so at the very least we would have to suppose that the two kinds of motion have very different chromatic sensitivities. Furthermore, from these data alone we cannot rule out mediation by a mechanism which receives mixed chromatic and luminance inputs. This seems unlikely, however, in view of our previous results showing that the motion of chromatic stimuli, although masked by luminance noise, exhibited very little susceptibility to chromatic noise masking suggesting it was mediated solely by luminance signals (Mullen et al., submitted; Yoshizawa et al., 2000b).

While our results showed no luminance masking of unsigned chromatic motion, the highest mask contrast available to us was also constrained by the technical limitations mentioned above. Thus it is possible that a more powerful luminance mask might have impaired unsigned chromatic motion. However, since our masking noise was sufficient to produce clear deterioration of signed chromatic motion, it seems unlikely that it would be too weak to affect unsigned motion.

An analogous use of chromatic noise masking can be more difficult because such a masker inevitably contains some luminance artifact, and consequently gives less clear results. However results from our other studies using Gabor apparent motion (Yoshizawa et al., 2000a) and drifting sine-wave gratings (Mullen, Yoshizawa, & Baker, 2002; Mullen et al., submitted) show that chromatic noise masks linear chromatic (signed) motion, but has very little effect on linear luminance-defined motion, and also very little effect on nonlinear (unsigned) motion of either chromatic or luminance stimuli.

Our unsigned motion stimuli were presented at a lower effective velocity than the signed motion, as a necessary consequence of the different phase values of displacement required to obtain the two kinds of motion (Dobkins & Albright, 1993). We have made such comparisons for quasi-linear (signed) vs nonlinear (unsigned) motion, using two-flash apparent motion of chromatic Gabor function kinematograms (Yoshizawa et al., 2000a), in which velocities were equated by use of differing displacements and SOAs. These results showed the same pattern of results as at differing velocities, i.e.

that the effects of luminance masking noise were selective for the linear (i.e., signed) chromatic motion, and that differences in stimulus velocity could not account for the selectivity of the luminance noise. It is an open question whether it is more pertinent to equate velocity or temporal frequency. Here we opted for a compromise, by using somewhat differing values of temporal frequency for signed vs unsigned motion, to lessen what would have otherwise been a much greater disparity in velocity.

#### 4.1. Comparison to previous studies of signed and unsigned chromatic apparent motion

Our results in the absence of a luminance mask are directly comparable to those of Dobkins and Albright (1993), who did not employ luminance masking. Specifically, spatial displacements of a quarter cycle (Fig. 1a) in the absence of masking noise produced a motion percept in the signed direction in nearly 100% of trials (leftmost points in graphs of Figs. 2 and 3). By comparison, smaller spatial displacements gave a reliable motion percept in the unsigned direction, at least for long presentation times (leftmost filled circles in Fig. 4), again comparable to those used by Dobkins and Albright (1993). However as we added luminance masking noise at successively greater contrasts, the signed motion was eroded to a degree which was inversely related to the chromatic contrast of the stimulus, indicating the involvement of luminance mechanisms. The unsigned motion was robust with luminance noise. At shorter durations, unsigned motion cannot be obtained or even reverses to signed motion; whenever signed motion occurs, it is masked by increasing luminance noise contrast (Fig. 4).

Cropper and Derrington (1996) have also reported signed chromatic motion of sine-wave gratings. They used very brief presentations of two-flash apparent motion, and obtained their results in the presence of a sine-wave luminance mask. In our second set of experiments we attempted to replicate their experiments as closely as possible. Using the briefest presentation of two-flash motion that elicited reliable reports of direction of motion, we found motion perceived in the signed direction, but only at small values of luminance masking contrast. As the masking noise contrast increased, performance deteriorated, again indicating mediation by a luminance mechanism. The masker used by Cropper and Derrington (1996) was a flashed sine-wave grating of relatively low fixed contrast (around 3 times its detection threshold), which presumably was not as effective as our spatio-temporally dynamic and broadband masking noise whose contrast was systematically varied. In the light of these results, it seems likely that other reports of signed chromatic apparent motion obtained in the absence of a luminance mask may also have suf-

ferred from the intrusion of luminance artifacts (Morgan & Ingle, 1994; Papatomas et al., 1991).

#### 4.2. Contribution of luminance mechanisms to signed chromatic motion

Wavelength dependent delays in the visual response to flicker are well established in the literature (de Lange Dzn, 1958; Lindsey, Pokorny, & Smith, 1986; Swanson, 1994; Swanson, Pokorny, & Smith, 1987; Swanson, Pokorny, & Smith, 1988; Walraven & Leebeek, 1964). Psychophysical studies (Stromeyer et al., 1995, 1997, 2000; Tsujimura et al., 1999, 2000) have demonstrated that temporal delays in the luminance system occur between stimulus components detected exclusively by L or M cones. These delays, however, do not originate in the cones themselves, since they are found only in the luminance system and not in the M/L cone opponent system, but reflect delays between cone responses as they are combined into a luminance channel. There is good evidence that these arise early in the visual system since the effects are monocular and apply to either flicker or motion. Moreover, similar shifts have been measured in retinal magnocellular cells of primates (Smith, Lee, Pokorny, Martin, & Valberg, 1992), suggesting a likely M-cell origin and an M-cell model of cone selective delays has also been proposed (Stromeyer et al., 1997). Alternatively, luminance signals might arise from chromatic stimuli through the scatter of isoluminant points across the population of M-cells (Cavanagh & Anstis, 1991; Logothetis, Schiller, Charles, & Hurlbert, 1990). In any case, motion information mediated by such luminance signals would then be vulnerable to luminance noise masking, as we have demonstrated here for signed chromatic motion. This interpretation is consistent with the proposal by Dobkins and Albright (1993, 1994), that M-cells contribute to signed chromatic motion perception.

Our experiments reported here were limited to red–green stimuli, and we cannot draw any conclusions about the existence or nature of signed chromatic motion with blue–yellow stimuli. If the basis of luminance signals arising from chromatic stimuli is the temporal delay between L- and M-cones, it is possible that different results might be obtained with blue–yellow stimuli.

#### 4.3. Nature of unsigned chromatic motion

We found that unsigned chromatic motion is fragile at shorter presentation times, even in the absence of luminance noise (Fig. 4). This dependence on duration is not seen for signed chromatic motion (Fig. 5), and together with the difference in vulnerability to luminance noise suggests that signed and unsigned chromatic motion are mediated by different mechanisms. There are

two candidate types of perceptual processing for unsigned chromatic motion, which might explain its reliance on long durations: a second order processing mechanism, or an attentional tracking.

Since by definition unsigned chromatic motion discards the chromatic polarity of contours, it must involve a nonlinear operation (such as full-wave rectification) on its chromatic inputs. This nonlinearity of processing, together with the lack of effect of luminance noise, suggests that unsigned chromatic motion is mediated by second-order processing of the kind explored in our previous work on two-flash Gabor kinematograms (Baker et al., 1998; Yoshizawa et al., 2000a). A possible physiological substrate might be the frequency-doubling behavior of M-cells (e.g., Lee, Martin, & Valberg, 1989), as proposed by Dobkins and Albright (1994); however this seems unlikely in view of the lack of masking by luminance noise. The requirement of long durations shown here (Fig. 4) might be understood in terms of the generally slower temporal processing of second-order motion described in other studies (e.g., Boulton & Baker, 1993; Mareschal & Baker, 1998; Smith & Ledgeway, 1998).

On the other hand, the dependence on long presentation times might be indicative of mediation, not by a low-level motion mechanism, but instead by eye movements or an attentional tracking capability. Since our observers were instructed to maintain fixation on a central fixation mark, it seems unlikely that eye movements were involved in tracking the stimulus motion; however we cannot rule out a contribution from attentional tracking which becomes effectively engaged only with longer stimulus durations. Previous work indicated a role of attentional tracking in signed chromatic motion (Seiffert & Cavanagh, 1999), but this issue has not been explored for unsigned motion. Seiffert and Cavanagh (1999) suggested that motion of isoluminant chromatic gratings (signed motion) is mediated by position-tracking when stimulus contrast and velocity are low, but by a low level, motion-energy mechanism at high contrast and high speed of stimuli. Since we did not examine effects of contrast or velocity on unsigned chromatic motion, and they did not evaluate dependence on duration, this possibility cannot yet be fully evaluated.

For achromatic apparent motion, Bex and Baker (1999) used a masking method to demonstrate an attentional tracking contribution for motion of random Gabor kinematograms, which occurred only at relatively large values of interstimulus interval (ISI). Since larger ISI values also produce a longer total presentation time, this result is consistent with an attentional tracking contribution to these results at longer durations.

Another possible explanation for the requirement of long stimulus durations for unsigned motion is depicted

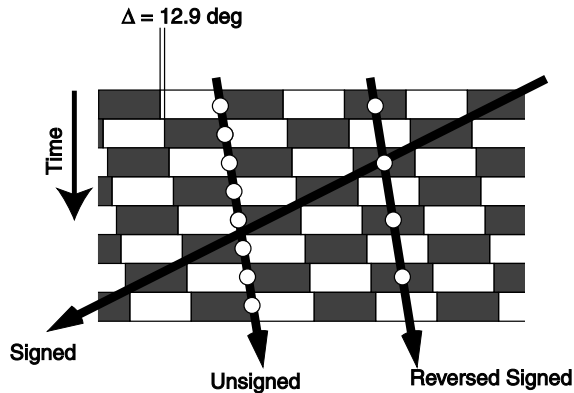


Fig. 6. Schematic spatio-temporal representation of a stimulus and possible kinds of motion percepts (arrows). In this case a signed-direction motion is leftward, and an unsigned or reversed-signed motion is rightward. Open circles on arrows represent tokens for motion correspondence.

by Fig. 6. Open circles on arrows represent possible tokens for motion correspondence. Such a motion mechanism might be particularly impaired at shorter durations. For example, in the case of a duration of 0.27 s (at which both observers failed to see unsigned motion), the stimulus would consist of just four frames; if every two frames are skipped because of a different chromatic sign between adjacent frames, there remain only two frames to establish motion correspondence. On the other hand, at 1.6 s duration (where subjects reported good unsigned direction motion) there are 12 frames even if half of the frames are skipped, which could provide more robust motion correspondence.

The present experiments by themselves do not conclusively indicate whether unsigned chromatic motion is mediated by a nonlinear chromatic motion mechanism or by an attentional tracking process, but do show that it is genuinely chromatically mediated, unlike signed chromatic motion.

## 5. Conclusion

Evidence in the literature suggests that the motion of chromatic stimuli under linear (first order) conditions is mediated largely or solely by luminance based signals, which we have termed temporal chromatic aberration. Yet this is seemingly at odds with previous reports of signed motion from chromatic stimuli. We find that the signed motion of chromatic stimuli is susceptible to luminance noise masking, providing a sufficiently high mask contrast is used. We thus conclude that signed motion is mediated by luminance based signals under the range of conditions that we have investigated. In comparison, unsigned motion is robust to luminance noise indicating that it is genuinely chromatic.

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