Perceived velocity of moving chromatic gratings

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Equiluminous red–green sine-wave gratings were drifted at a uniform rate in the bottom half of a 10-deg field. In the top half of the display was a sinusoidal-luminance grating of the same spatial frequency and 95% contrast that drifted in the opposite direction. Observers, while fixating a point in the display center, adjusted the speed of this upper comparison grating so that it appeared to match the velocity of the chromatic grating below. At low spatial frequencies, equiluminous gratings were appreciably slowed and sometimes stopped even though the individual bars of the grating could be easily resolved. The amount of slowing was proportionally greatest for gratings with slow drift rates. Blue–yellow sine-wave gratings showed similar effects. When luminance contrast was held constant, increasing chrominance modulation caused further decreases in apparent velocity, ruling out the possibility that the slowing was simply due to decreased luminance contrast. Perceived velocity appears to be a weighted average of luminance and chrominance velocity information.

Zeki[1] has suggested that the analysis of motion may involve one particular area of the prestriate cortex, whereas the analysis of color may involve another area. In the macaque monkey, whose visual system closely resembles that of man, color-coded cells are found principally in area V4, whereas direction-specific cells are found in the medial posterior bank of the superior temporal sulcus. If, as Zeki suggests, the cells of the movement area are not concerned with color and the cells of the color area are not concerned with movement, then the perception of motion of stimuli defined solely by color should pose problems for the visual system.

Motion perception is degraded for chromatic stimuli under equiluminous conditions.[2,3] Although the extent of the degradation varies with stimulus conditions,[4] it has always been found to some degree. The question arises whether the degradation is simply a failure of motion perception (as, for example, in the upper displacement limit for apparent motion) or whether it also involves a reduction in the perceived velocity of the motion.

The experiments that we report here evaluate the perceived velocity of drifting chromatic gratings at a range of luminance contrasts around the equiluminance setting. Moreland[3] has reported that colored gratings appear to slow down noticeably at equiluminance. Thompson,[5] however, has reported that luminance gratings also slow down when their contrast is reduced, at least at temporal rates below 4 Hz. In the experiments that follow, we measured the slowing of equiluminous gratings and showed that it is a specific property of the chrominance mechanisms[6] and not a result of the lower "effective" contrast of a chromatic grating.[7]

METHODS

The stimuli used in our experiments were sinusoidal gratings modulated in both color [red–green or blue–yellow; see Fig. 1(a)] and luminance. They were generated by a 512 × 512 resolution graphics system and displayed on a Conrac 5411 monitor. The x and y Commission Internationale de l'Eclairage (CIE) coordinates of the phosphors[8] were 0.60 and 0.35 for red, 0.29 and 0.60 for green, and 0.15 and 0.07 for blue. The display subtended 10 × 10 deg of visual angle at the 140-cm viewing distance.

The chromatic gratings were generated by superimposing red and green (or blue and yellow) sinusoidal gratings 180 deg out of phase. Chrominance modulation was defined as the amplitude of the chromaticity change in CIE coordinates as a percentage of the maximum change possible between the red and green phosphors [Fig. 1(a)] or between the blue and the combined output of the red and green phosphors (yellow, x and y CIE coordinates 0.49 and 0.44, respectively). Since the red and green modulations are 180 deg out of phase, the luminance modulation can be expressed as the difference between their two amplitudes, R_{mod} and G_{mod}, divided by the mean luminances of the two wave forms R and G:

$$\text{Luminance modulation} = (R_{\mathrm{mod}} - G_{\mathrm{mod}})/(\overline{R} + \overline{G}). \quad (1)$$

An arbitrary 0% luminance modulation was defined for each subject by equalizing red and green luminances for a 10-deg field with flicker photometry at 15 Hz. Since both gratings were calibrated to be true sinusoidal modulations of luminance on the monitor screen, their sum at any phase of the

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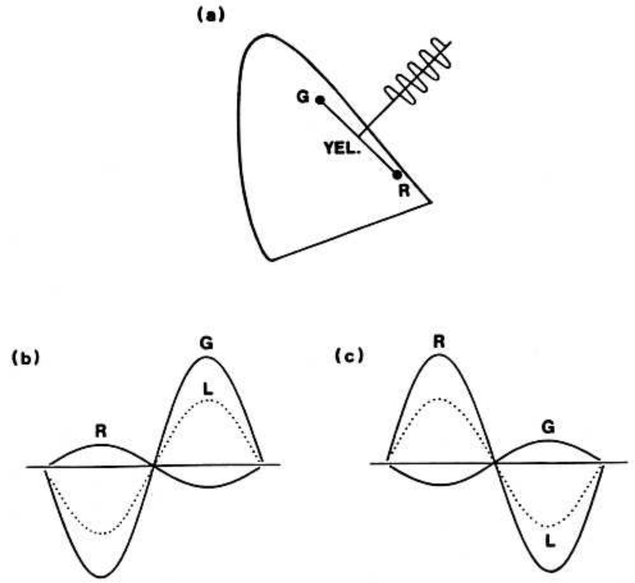

Fig. 1. (a) The red–green chrominance modulation varied about the point Yel in the CIE diagram, reaching chromaticities G and R at maximum modulation (100%). The blue–yellow modulation varied in a similar fashion about a point midway between the blue phosphor and the Yel chromaticity shown here. (b) Red (R) and green (G) wave forms with red modulation less than green resulting in a luminance modulation (L) that is arbitrarily labeled negative [see Eq. (1)]. (c) As in (b), but green modulation less than red; luminance modulation labeled positive in this case.

cycle produces a constant luminance value if both red and green sine waves have the same luminance-modulation amplitude. Shifts of the true equiluminance point away from the arbitrary zero value (because of possible spatial[9] or temporal[10] frequency effects) produce a simple shift of the luminance scale. Luminance modulation had both positive and negative values; positive values were arbitrarily chosen to represent the case in which the red modulation amplitude was greater than the green, and negative values were chosen to represent the reverse. A red–green grating of 70% chrominance modulation and 10% luminance modulation, for example, would vary from a yellow-green to a slightly more luminous yellow-orange, whereas 70% chrominance and −10% luminance modulation would vary from yellow-orange to a slightly more luminous yellow-green [Figs. 1(b) and 1(c)]. A 0%-chrominance 10%-luminance red–green grating would vary from light to dark yellow. The chrominance modulation that we have defined as 70% is about 32% of the maximum chromaticity modulation that can be obtained on the CIE color triangle.

The displays had a mean luminance of 26 cd/m^2. The upper and lower gratings were separated by a 2-deg horizontal strip across the entire display that had the same mean luminance as the gratings. The display was presented within a fixed aperture on a black background.

The display image was optically diffused with a frosted acetate sheet having a blur circle with half-width at half-amplitude of 1 mm (0.02 deg of visual angle for the viewing distance used). This sheet filtered out spatial frequencies starting at about 10 cycles per degree [(cpd); amplitude halved at 25 cpd], attenuating, in particular, the spatial frequency of the sampling rate of the 512×512 pixel display (50 cpd) and also eliminating screen reflections. The highest spatial frequency used in the experiment was 3.2 cpd. Each sine-wave cycle was presented in 16 discrete luminance and chrominance steps. The transitions created by this sampling were below threshold for all chromatic[11] and low-modulation-luminance[12] gratings and were only just visible for the high-contrast (95%) luminance comparison grating in the lowest spatial-frequency condition (0.4 cpd; see Fig. 4). A control experiment showed that the visibility of these transitions in the adjustment grating did not affect the settings. The raster rate was 30 Hz, and all movement steps were presented in integral multiples of 33.3 msec. The temporal frequency of the test gratings in the experiments varied from 0.12 to 7.5 Hz and appeared as smooth movement for all the spatial frequencies and contrasts that were used.[13]

A sinusoidal-luminance grating of 95% was presented in the top half of the display, and a test sine-wave grating of variable chrominance and luminance modulation was presented below. The comparison grating was always set to the same spatial frequency as the test grating. The two gratings moved in opposite directions to eliminate any obvious cue for matching their speeds and to minimize cues for tracking eye movements. The chromatic test grating drifted at a fixed velocity determined by the experimenter, and the comparison luminance grating drifted at a velocity controlled by the observer. The observer's task was to match the perceived velocity of the two gratings while maintaining fixation on a fixation spot centered between the two gratings. To prevent the buildup of a motion aftereffect, the directions of the gratings reversed after each setting.

A control was run to ensure that the movement of the high-contrast comparison grating on top did not produce any induced movement in the low-contrast test gratings at the bottom. Observers were asked to null any motion that they perceived in the bottom grating while the top grating drifted at 1.2 deg/sec. Both test and comparison gratings were 0.8 cpd, and the test grating had 4% luminance modulation and 0% chrominance modulation. No induced motion was found. Similarly, when the observers were asked to match the speed of the top and bottom gratings just described, the speed match was the same whether the top and bottom gratings moved in the same or in opposite directions, indicating that no induced motion was produced.

Four observers participated in the experiment, the three authors and one naive, paid observer. The vision of all observers was normal or corrected, and no color deficits were detected.

RESULTS

Velocity Judgments

Red–green gratings were drifted at 0.3, 1.2, and 4.8 deg/sec. The chrominance modulation was 70%, and the spatial frequency was 0.8 cpd. Observers made at least four velocity matches for each of several luminance modulations between −16% ($G_{\mathrm{mod}} > R_{\mathrm{mod}}$) and +16% ($R_{\mathrm{mod}} > G_{\mathrm{mod}}$). The comparison grating had the same spatial frequency as the test.

The results (Fig. 2) are plotted in terms of relative speed, that is, the perceived velocity, as judged by the setting of the comparison grating divided by the actual test velocity. All three observers in this condition showed a pronounced slowing of perceived velocity. The relative slowing was greatest for the slowest test velocity; the test occasionally appeared to be

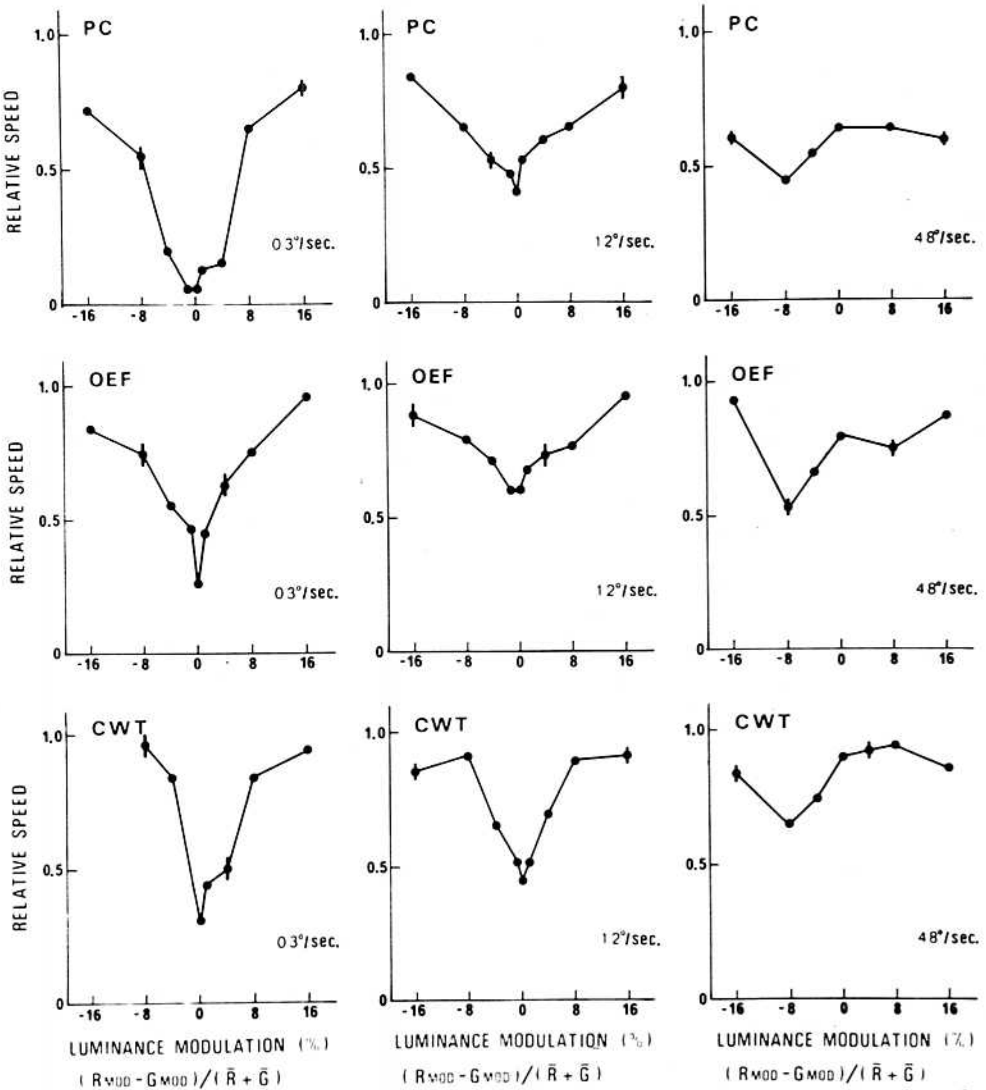

Fig. 2. Relative speed of a red–green test grating (the speed of a black–white comparison grating set to perceptual match with the test divided by the actual test speed) as a function of luminance modulation at three test speeds for observers PC, OEF, and CWT. Spatial frequency was 0.8 cpd.

stationary in this condition. The average relative speed across observers was 0.21 for 0.3-deg/sec test velocity, 0.48 for 1.2 deg/sec, and 0.53 for 4.8 deg/sec.

The minimum-motion point occurred at the preset equiluminance point for the two slower speeds, but significantly more green modulation was needed to reach the minimum-motion point at the highest speed for all three observers.

Blue–Yellow

The previous experiment was repeated using 70%-chrominance-modulation blue–yellow sine-wave gratings at 0.8 cpd that drifted at 1.2 deg/sec. Again, for both subjects in this condition, a significant slowing (Fig. 3) in relative speed was observed that was similar in magnitude to that for the comparable red–green condition.

The minimum-motion point required 4 to 8% more blue modulation than was necessary for the minimum-flicker point (the preset 0% luminance point). This is consistent with the lower efficiency of blue input to the luminance channel at higher spatial frequencies reported by Anstis and Cavanagh.[9] Since the preset 0% luminance point is established by 10-deg uniform field flicker while the test gratings are at 0.8 cpd, a substantial shift of the equiluminance point toward blue is to be expected.

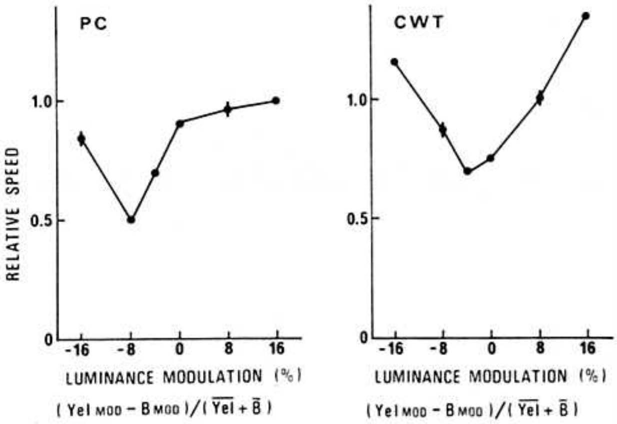

Fig. 3. Relative speed of a blue–yellow test grating as a function of luminance modulation for observers PC and CWT. Spatial frequency was 0.8 cpd, and test speed was 1.2 deg/sec.

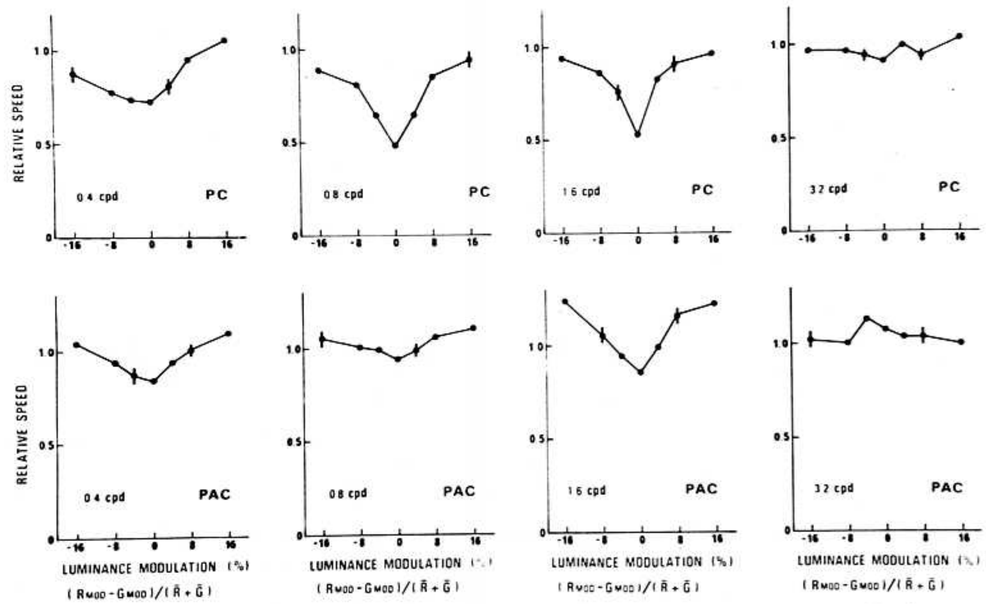

Fig. 4. Relative speed of a red–green test grating as a function of luminance modulation and spatial frequency for observers PC and PAC. Test speed was 1.2 deg/sec.

Spatial Frequency

Red–green test gratings of four spatial frequencies, 0.4, 0.8, 1.6, and 3.2 cpd, were drifted at 1.2 deg/sec. The gratings all had 70% chrominance modulation. The comparison gratings always had the same spatial frequency as the test.

Consistent minima were found for the three lower spatial frequencies at the 0% luminance modulation (Fig. 4). The minima were rather weak and broad at the lowest spatial frequency, 0.4 cpd. The minimum was similarly weak at 0.8 cpd for observer PAC, although this condition generally gave a strong slowing for other observers (Fig. 2). At the highest spatial frequency, 3.2 cpd, no reliable minimum was ever observed.

The slowing appears to be limited to low-frequency gratings and could not be obtained for tests of 3.2 cpd or higher or for square-wave tests. Luminance artifacts do not seem to play a role in the velocity perception under these conditions. Chromatic aberration for a red–green grating at 3.2 cpd is minimal, and observing the displays with an achromatizing lens did not affect the settings. Phase shifts between the red and green responses[14,15] were not a factor either, as no readjustment of the phase angle between the two sine waves produced any further slowing of perceived velocity.

Luminance Contrast

Luminance test gratings (light and dark yellow) of 0% chrominance modulation and 0.8 cpd were used to evaluate the perceptual slowing seen for low-contrast luminance tests at three test speeds, 0.3, 1.2, and 4.8 deg/sec. Low chrominance modulation (7%, red–green) tests were also evaluated to see how a small chrominance signal would affect the perceived velocities.

The results (Fig. 5) show a moderate decrease in perceived velocity as the test luminance modulation decreased from 16 to 1%. No systematic differences are seen among the three test speeds for the two observers. Averaging the relative velocities across the three speed conditions and the two observers shows a drop in the relative perceived speed from 0.96 at 16% modulation to 0.69 at 1% modulation (the comparison grating had 95% modulation).

When the test gratings had 7% chrominance modulation, the results appear roughly similar to those for the luminance-only grating, with the exceptions that the readings could be taken for both positive (red modulation greater than green) and negative (green greater than red) luminance modulations as well as luminance modulation of zero. The results for positive and negative luminance modulation are quite similar—the dashed curves (Fig. 5) are basically symmetrical. The velocity matches for the chromatic gratings at the equiluminance point are substantially lower than those for the comparable gratings of 70% chrominance modulation (Fig. 2).

To summarize, gratings with low chrominance modulation are perceived to move slowly, if at all, at equiluminance. Their perceived velocity when any luminance modulation is added appears to be determined by the luminance modulation alone. In the next experiment we evaluated the effect of varying the chrominance modulation on the perceived velocity of gratings with low luminance modulation.

Summation of Chrominance and Luminance Signals

The test gratings were red–green sine-wave gratings of 4% luminance modulation at 0.8 cpd drifting at 1.2 deg/sec. Their chrominance modulation was varied from 64% (green modulation slightly greater than red, arbitrarily labeled negative on Fig. 6) through 0% (light and dark yellow) to 64% (red modulation slightly greater than green). In all cases the resulting luminance modulation was 4%.

The results for both observers (Fig. 6) show that the addition of chrominance modulation to a luminance grating slows down its perceived velocity. Clearly, for high levels of chrominance modulation, perceived velocity is not a simple function of luminance modulation or of "effective" luminance contrast of the chrominance signal.[7] As the chrominance modulation is increased, the two colors become more distinct, and yet their perceived velocity decreases.

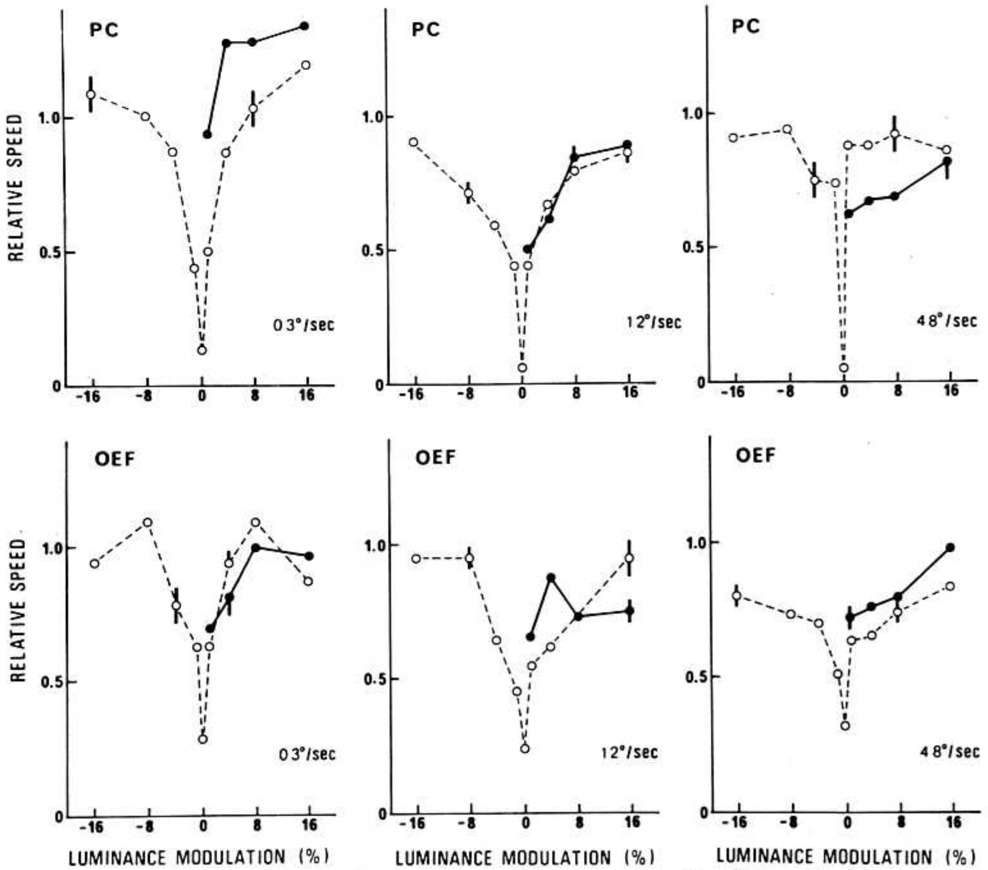

Fig. 5. Relative speed of a yellow luminance grating (●) and a 7% red–green chromatic grating (○) as a function of luminance modulation and test speed for observers PC and OEF. Spatial frequency was 0.8 cpd.

Velocity

It was observed in the first experiment that the luminance ratio setting for the minimum-motion judgment required more green modulation at the highest test velocity (4.8 deg/sec). In the next experiment, this shift was evaluated at two different spatial frequencies to determine if this was an effect of temporal frequency or of velocity. Red–green gratings of 0.4 and 1.6 cpd drifted at three speeds, 1.2, 2.4, and 4.8 deg/sec. All gratings had 70% chrominance modulation.

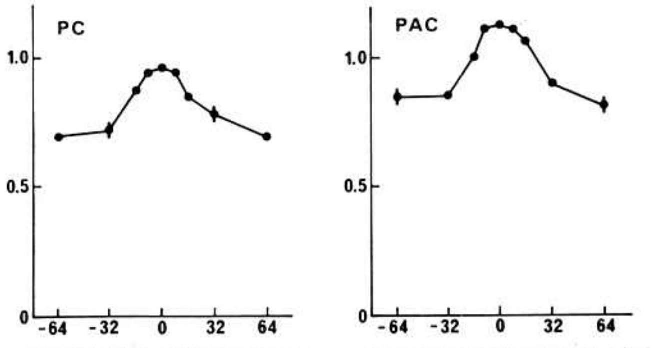

Fig. 6. Relative speed of a 4% luminance grating as a function of its red–green chrominance modulation for observers PC and PAC. Spatial frequency was 0.8 cpd, and test speed was 1.2 deg/sec. Negative chrominance modulation indicates that green modulation was greater than red.

The results (Fig. 7) show that for both spatial frequencies, as speed increased, the minimum-motion point requires more green modulation. Since the two test frequencies differ by two octaves, the shift cannot be a function of the temporal frequency but must be a result of a velocity factor. Other contributing factors that would have varied with either temporal or spatial frequency, such as phase lag or chromatic aberration, can equally be ruled out by these data.

DISCUSSION

The perceived velocity of equiluminous gratings is substantially slowed at low spatial frequencies. The gratings often appear to stop even though their bars are clearly resolved. In these instances, the motion is appreciated only because it is occasionally noticed that the bars are at some new position. Other examples of such motion standstill have been reported for black and white stimuli in the periphery by Campbell and Maffei[16] and by others.[17–19] In the experiments reported here, the stimuli extended from 1 to 4 deg into the periphery, but the phenomenon could be observed with central fixation as well.

Campbell and Maffei[16] have also reported that high-spatial-frequency gratings appear slowed when compared with low-spatial-frequency gratings. In our experiments, the test and comparison gratings were always at the same spatial frequency so that the slowing that we observed is in addition to any variation specific to spatial frequency.

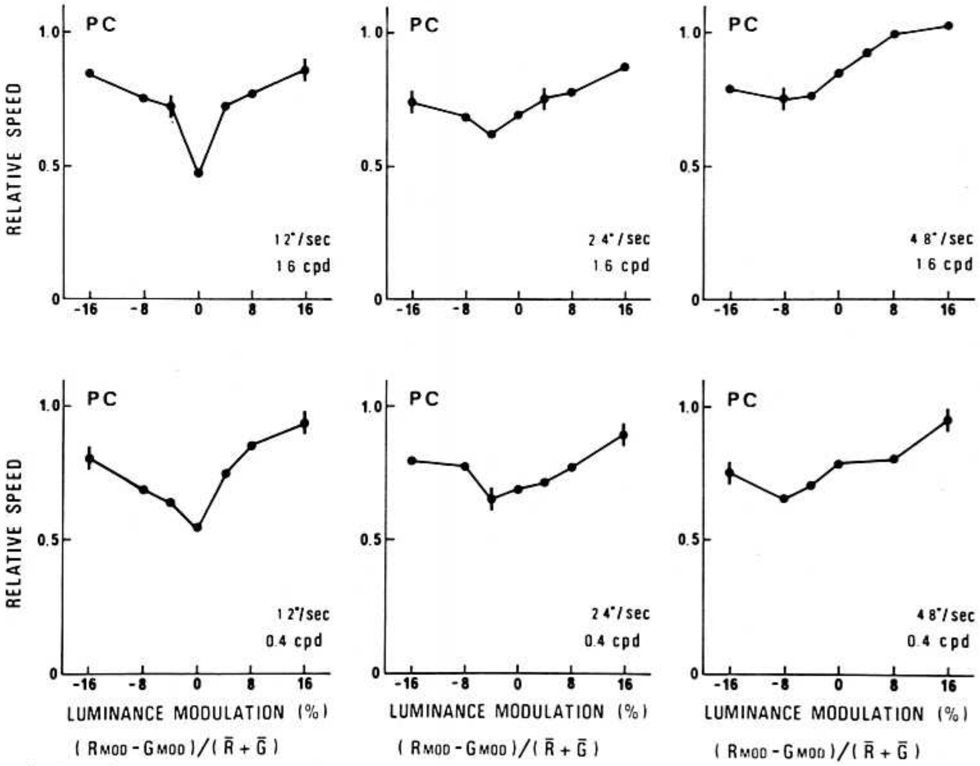

Fig. 7. Relative speed of a red–green test grating as a function of luminance modulation for three test speeds and two spatial frequencies. Observer PC.

We observed slowing only at low spatial frequencies (less than 3.2 cpd). However, it is possible that the chromatic gratings are slowed at all spatial frequencies but that black-and-white gratings are similarly slowed only at high spatial frequencies, as Campbell and Maffei report. Since our comparison was a black-and-white grating we would therefore observe slowing of chromatic gratings only for low frequencies. An alternative possibility is that motion for low spatial frequencies is signaled by a transient system and that for higher spatial frequencies by a sustained system.[20] The sustained system would be capable of responding to chromatic stimuli, and the transient system would not.

It is clear from our fourth experiment that the chromatic gratings do not appear slowed because of their low "effective" contrast. As we added chrominance modulation, thus necessarily increasing the effective contrast, perceived velocity actually decreased. It would appear that the perceived velocity is derived from a weighted sum of the separate color and luminance analyses of the stimulus, the analysis for color signaling a much lower velocity. With increasing chrominance modulation, this low-velocity estimate is given more weight relative to that for the luminance modulation, and the grating slows down.

Figure 8 depicts one possible source of the lower-velocity judgments for chromatic stimuli. Although we did not measure velocity thresholds, it was clear that they were significantly higher for the chromatic gratings than for the luminance gratings. The motion of equiluminous gratings was frequently impossible to detect at velocities of 0.3 deg/sec; motion thresholds for luminance gratings, however, are more of the order of 0.03 to 0.06 deg/sec (Ref. 21) at these spatial frequencies. Figure 8 presents hypothetical curves of actual versus perceived velocities for chrominance and luminance gratings. The higher-velocity threshold for the chromatic grating is seen in the rightward shift of its intercept. A chromatic grating moving marginally slower than this threshold velocity is not seen to move at all, whereas the luminance grating at this same velocity is perceived to move almost at its actual speed. If the chromatic grating never regains this speed difference as velocity increases, then the chromatic grating will always be observed to be slower (e.g., the two velocities circled on Fig. 8), although, in relative terms, the amount of slowing will decrease. This uncompensated threshold loss appears to describe our data reasonably well.

It is interesting to compare this hypothesis with the response of the visual system to stimulus contrast. Contrast threshold varies significantly as a function of spatial fre-

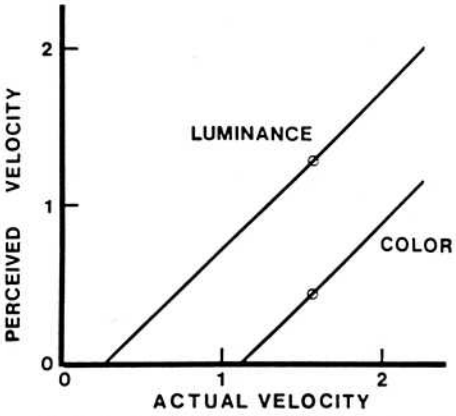

Fig. 8. Hypothetical relations between actual velocity and perceived velocity for chromatic and luminance gratings showing a higher motion threshold and an increase in perceived velocity for the color stimulus that parallels that for the luminance stimulus.

quency, but the visual system effectively compensates for these threshold differences at suprathreshold levels.[22] Perhaps equiluminous stimuli are simply not encountered often enough for the visual system to develop a compensation for velocity underestimation.

ACKNOWLEDGMENTS

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11. Fourier analysis of this stepped stimulus shows that the transitions produce upper harmonics at multiples of 15, 17, 31, 33, etc. of the fundamental frequency, each nth harmonic having an amplitude of $1/n$ of the fundamental. The lowest frequency used here was 0.4 cpd at 70% chrominance modulation, so its lowest harmonic was 6 cpd at 4.6% modulation. According to Ref. 10, Fig. 2, the threshold for this component is about 10%. Even the sums of the fifteenth and seventeenth harmonics do not reach threshold in this worst-case stimulus.
12. Similarly, the luminance component of the transition varied from 0 to 16% in amplitude. Its upper harmonics, therefore, will all be lower than 1% amplitude, whereas the luminance contrast threshold is greater than 1% at all these harmonics (Ref. 10, Fig. 8). At all higher test spatial frequencies, the upper harmonics resulting from the transitions are even further below their thresholds, both because the thresholds increase with spatial frequency and because the diffusion sheet begins to reduce their amplitude.
13. The upper temporal harmonics of an interlaced 30-Hz presentation start at 22.5 Hz and 0.38 of the fundamental amplitude for the highest temporal rate used here (7.5 Hz). Lower temporal rates in the stimuli permit more samples per cycle, and the lowest upper harmonic is consequently at a higher temporal frequency (i.e., greater than 22.5) and lower amplitude. The fundamental amplitude of 70% chrominance and 16% luminance modulation produces upper harmonics of 26.6% chrominance and 6.1% luminance modulation, both of which are below their respective thresholds at 22.5 Hz.
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