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Spatial frequency discrimination: a comparison of achromatic and chromatic conditions

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Abstract

In this study, we have compared foveal SF discriminations for luminance and color-defined stimuli using two different tasks (criteria): in *criterion-A*, the discrimination is based on spatial (size of the stimuli) and/or spatial frequency; in *criterion-B*, it is based on apparent motion (contraction/expansion). We used high contrast (75%) spatially localized D6 stimuli and cosine gratings (0.25–9.5 cpd). The SF discrimination was measured by the method of constant stimuli with a two-interval forced-choice procedure. Data show that: (i) for *criterion-A*, the discrimination thresholds for color stimuli were lower than that for luminance stimuli at low SFs, but similar or higher at higher SFs; for *criterion-B*, the thresholds to chromatic stimuli were higher than that to achromatic stimuli for all SFs; (ii) SF discrimination was best at inter-stimulus-interval (ISI) of about 200 ms for color stimuli and at ISI of 0 ms for luminance stimuli; (iii) SF discrimination got better with stimulus duration and reached to plateau at 200 ms (or more) for color stimuli and at 67 ms (or more) for luminance stimuli; (iv) SF discrimination threshold (mean $\Delta f = 0.19$ octaves) is about one-tenth of the full bandwidth (mean = 1.96 octaves) of SF tuned mechanisms and is in hyperacuity range; both (discrimination and hyperacuity) can be explained by the relative activities within a population of tuned mechanisms. We conclude that color and luminance SF discrimination thresholds have a different SF dependence. While color appears to perform better than luminance vision at low SFs, this effect is lost or even reversed at high SFs. Data imply that color and form interact, but color and motion are largely segregated (i.e. they weakly interact). © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Suprathreshold; Color-defined form; Luminance-defined form; Luminance and color apparent motion; Relative activity of tuned mechanisms; Hyperacuity

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1. Introduction

Spatial frequency (SF) discrimination is an important psychophysical measurement to investigate the spatial processing of chromatic and achromatic stimuli at suprathreshold levels; discrimination task complements the detection task. Investigators measured SF discrimination at photopic (Campbell, Nachmais, & Jukes, 1970; Hirsch & Hylton, 1982, 1985; Regan, Bartol, Murray, & Beverley, 1982; Regan & Beverley, 1983, 1985; Burbeck & Regan, 1983; Wilson & Gelb, 1984; Wilson & Regan, 1984; Westheimer, 1984, 1985; Hirsch, 1985; Regan, 1985, 1989; Mayer & Kim, 1986; Regan & Price, 1986; Bradley, Skottun, Ohzawa, Sclar, & Freeman, 1987; Skottun, Bradley, Sclar, Ohzawa, & Freeman, 1987; Webster, De Valois, & Switkes, 1990; Greenlee & Thomas, 1992) and scotopic (Vimal & Wilson, 1987) levels for luminance-defined forms. In addition, several researchers have looked at spatial acuity tasks for chromatic and luminance stimuli (Krauskopf & Farell, 1991; Martini, Girard, Morrone, & Burr, 1996; Rovamo, Kankaanpaa, & Kukkonen, 1999; Wuerger & Morgan, 1999). However, very little SF discrimination data for color-defined form (Webster et al., 1990) and none for apparent-motion task are available; this fact is also mentioned in Regan (2000). Webster et al. (1990) measured SF discrimination thresholds for color and luminance-defined forms at SFs 0.5–4 cpd and concluded that color vision is deficient compared to luminance vision in SF discrimination.

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However, this cannot be generalized for all SFs because data at other SFs are missing. Furthermore, perception of form may include SF, orientation, edges, boundaries, contour, and so on. The idea that color vision is deficient in form perception is controversial (e.g. Livingstone & Hubel, 1987; Mullen, Beaudot, & McIlhagga, 2000). Mullen et al. (2001) reported that color and luminance channels perform similarly on contour integration over a wide range of curvatures. Thus, the processing of color and form is an important topic that requires further investigation. For these reasons we have measured SF discrimination for red–green chromatic vision and compare with that for achromatic vision using a very large data set (0.25–9.5 cpd in 0.25–0.5 octave steps). That is, we have measured and compared SF discrimination for: (i) color-defined form; (ii) luminance-defined form; (iii) chromatic apparent-motion task; and (iv) a luminance apparent-motion task.

For this purpose, two criteria for SF discrimination were used. In *criterion-A* (500 ms interval or duration, 500 ms ISI), SF discrimination was based on spatial (size of the stimuli) and/or spatial frequency. Observers were required to report the interval containing 'lower SF and/or larger size pattern' in a two-interval-forced-choice procedure. *Criterion-A* was used to measure SF discrimination for color and luminance defined forms. In general, we found better SF discrimination for color-defined form than that for luminance-defined form at low SFs, and similar to worse discrimination for color-defined form at higher SFs.

In *criterion-B* (500-ms interval, 0 ms ISI), SF discrimination was based on the apparent motion; subjects found this task easier and they did not use *criterion-A* for this task. The zero inter-stimulus-interval produces an apparent motion of contraction if the second interval has higher SF and apparent expansion if the second interval has lower SF. *Criterion-B* was used to measure SF discrimination for chromatic apparent-motion and luminance apparent-motion. We found that the SF discrimination was significantly better for luminance apparent-motion than that for the chromatic apparent-motion task, luminance-defined form, and color-defined form based on the common metric of *times threshold contrast*. Preliminary data were reported, in part, in Vimal (1988) and Vimal and Pandey (1989).

2. Methods

2.1. Apparatus

Stimuli were generated and controlled by an Adage-3006 color raster system interfaced with a PDP11/23-RT11 operating system and displayed on an Electrohome color monitor. Powell air-spaced achromatizing lens was used to correct chromatic aberration. Observers used a 5-mm artificial pupil and maintained the head position and the alignment with their dental bite bar. To make sure that the lens was aligned correctly, observers were instructed to minimize the fringes around the stimulus, keep the stimulus focused (not blurry), and not to move head and bite bar after best alignment. The alignment was repeatedly checked during the experiment. The observer's eye was mostly at 160 cm (80 cm for low SFs) from the color monitor screen; the left eye was used for observations and the right eye was patched.

2.2. Calibration

The color raster system and the color monitor were calibrated with a Pritchard photometer. The lookup table method was used for the calibration of red and green primaries because this method was found to be more accurate than the usual gamma-correction formulae (Cowan, 1983). In the lookup table method, the luminances of red, green, and blue phosphors were measured for 0–255 device values of red–green–blue guns in steps of 8; an interpolation technique was used to calculate luminances at other device values. The table contained the luminance of red, green, and blue phosphors for each device value of the respective red, green, and blue guns of the monitor. The blue primary was not used. The (x, y) chromaticities of the red and green phosphors of the Electrohome color monitor were $(0.620, 0.348)$ and $(0.291, 0.608)$, respectively.

2.3. Definition of red–green chromatic stimuli

The red–green chromatic channel was isolated by use of the minimum-flicker technique. A red pattern was flickered with a green pattern (mostly at 15 Hz), and the mean luminance of the red pattern was adjusted to achieve minimum flicker (Kaiser, Ayama, & Vimal, 1986; Kaiser, Vimal, Cowan, & Hibino, 1989; Vimal, 1997, 1998a,b, 2000, 2002). This allows us to measure red/green equiluminance ratio. Achromatic stimulus was defined by keeping red and green patterns in spatial inphase, and red–green chromatic stimulus was defined by placing red and green components of a pattern in antiphase.

2.4. Spatiotemporal characteristics of stimuli

The test and standard stimuli were vertical and localized in both spatial extent and SF content (full bandwidth at half amplitude of 1 octave). These are defined as a sixth spatial derivative of a Gaussian function (D6) (Vimal, 1997, 1998a,b, 2000, 2002). The test stimuli had the following luminance profile:

$$L(x) = L_o \,[1 + C\,\mathrm{D6}(x, \sigma)], \tag{1}$$

where L_o is the mean luminance, C is the stimulus contrast, and σ is the space constant in degrees of visual angle of the pattern. Stimulus contrast C is defined as the ratio of the maximum phosphor modulation in time and space to the mean phosphor luminance. Stimulus luminance contrast is expressed as,

$$C = [L_{\max} - L_{\text{mean}}]/L_{\text{mean}}, \tag{2}$$

where $L_{\max}$ is the maximum luminance of a red or green pattern in both space and time and L_{mean} is its mean luminance. Stimulus contrast was 75% in the SF discrimination experiment for all conditions. The stimulus contrasts of the red and green components co-varied. This means, the cone contrasts was 75% for luminance (inphase) stimuli. However, for chromatic (antiphase) stimuli, the root-mean-square (RMS) cone color contrasts were about 23.6% (RP) and 26.2% (RV) of the stimulus contrast C in Eq. (2) (Vimal, 1998b); thus RMS cone color contrasts (23.6–26.2%) were about one-third of RMS cone luminance contrast (75%). For comparing color and luminance SF discrimination, a common metric of *times threshold contrast* (8 or 20×) was used as described later in Sections 3.5 and 4.3. The rationale for using D6 stimuli was: (i) that a D6 spatial stimulus is localized in both spatial extent and SF content (full bandwidth at half amplitude of 1 octave); and (ii) the negative flanking lobes of D6 have smaller amplitude compared to the central lobe (Wilson, McFarlane, & Phillips, 1983), presumably this attribute more closely resembles receptive fields of cortical cells. The rationale for using cosine gratings (as a control experiment) was: (i) to investigate if there is significant pattern-type effect (D6 versus cosine); and (ii) to compare with the results of other investigations where cosine gratings were used.

Temporally, the stimuli were modulated by a Gaussian with a 0.25-s time constant with 0.5-s duration in each of two intervals. The viewing angle (horizontal × vertical) for D6 stimuli was mostly (4° for low SFs, 2° for higher SFs)$\times$0.5° on 6.4° diameter equiluminant inphase surround, and that for cosine gratings was 4° diameter on dark surround. The mean luminance of stimuli was about 26–27.8 cpd/m^2. For SF discrimination, SFs were 0.25–9.5 cpd in 0.25 or 0.5 octave steps. For CSF, SF ranged from 0.25–11.3 cpd. Even at the highest SF of 9.5 cpd used in discrimination experiments, subjects were able to see color at suprathreshold contrast of 75%. For CSFs, subjects were instructed to detect color with respect to a uniform background (Vimal, 1997, 1998a,b, 2000, 2002). Subjects were instructed to keep their eye aligned through the Powell's achromatizing lens (Section 2.1) to minimize the luminance artifacts due to transverse chromatic aberration (if eye was not aligned correctly, it was hard to see color pattern at high SFs).

2.5. Observers

The observers, RV (40-year-old male), RP (34-year-old female), and HH (28-year-old male) all had normal color vision as assessed by the Ishihara plates, and Rayleigh and Moreland equations (see Vimal, Pokorny, & Smith, 1987 for RV and RP). They had normal color discrimination on the Farnsworth Munsell 100-Hue Test and normal stereopsis on Titmus and TNO tests (see Vimal, Pokorny, Smith, & Shevell, 1989 for RV and RP). The observers were corrected to 20/20 normal vision. The space averaged luminance was: $11.6\text{R} + 14.4\text{G} = 26$ cpd/m^2 for observer RV; $11.9\text{R} + 14.4\text{G} = 26.3$ cpd/m^2 for RP; and $13.4\text{R} + 14.4\text{G} = 27.8$ cpd/m^2 for HH.

2.6. Procedure and observer's task

The discrimination was measured by the method of constant stimuli with two-interval forced-choice (2IFC) procedure. The zero inter-stimulus-interval produces an apparent motion of contraction if second interval has higher SF and apparent expansion if second interval has lower SF. The number of trials per data point was 500–3650; each session has 250 trials; 25 trials for each of five test SFs: two above, one at, and two below standard SF. Standard stimulus was randomly presented in one of the two intervals, and test in the remaining interval.

Initially, the observer was adapted to the mean luminance for a period of about 5 min. The observer's task was: (a) to initiate each trial with a button press; and then (b) to signal which interval had lower SF and/or larger size stimulus for *criterion-A*. For *criterion-B*, the observer was required to signal the first interval if the apparent motion of contraction was perceived, and signal the second interval if apparent expansion was perceived. This is equivalent to signaling which interval has lower SF pattern.

3. Results and data analysis

3.1. Color and luminance contrast sensitivity functions

The color contrast sensitivity functions (CSFs) are low-pass and the luminance-CSFs are bandpass functions of SF (Fig. 1). The color-CSFs were measured with 4° (or 2°)$\times$0.5° D6 equiluminant inphase surround and luminance-CSFs were measured with 4° D6 stimuli on dark surround. The average of the right half bandwidths of color CSFs is 3.2 octaves (SE = 0.8) from 0.25 cpd. The luminance CSFs peak at approximately 2 cpd (on average); their average full-bandwidth at half-height is about 4.7 octaves, consistent with Vimal (1998b).

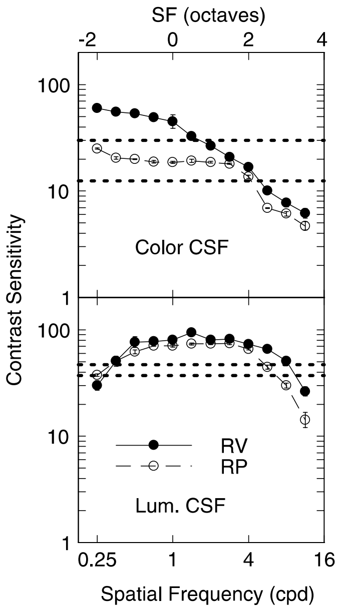

Fig. 1. *Upper graph*: Color contrast sensitivity function (CSF) (stimulus color contrast sensitivity versus spatial frequency (SF)). *Lower graph*: luminance CSF (luminance contrast sensitivity versus SF). Filled circles joined with solid lines represent data for RV and open circles joined with dashed lines for RP. Error bars are 1 standard error of mean (SE). The color-CSFs are a low-pass and the luminance-CSFs are a bandpass function of SF. The dashed lines are drawn at half of the maximum contrast sensitivities.

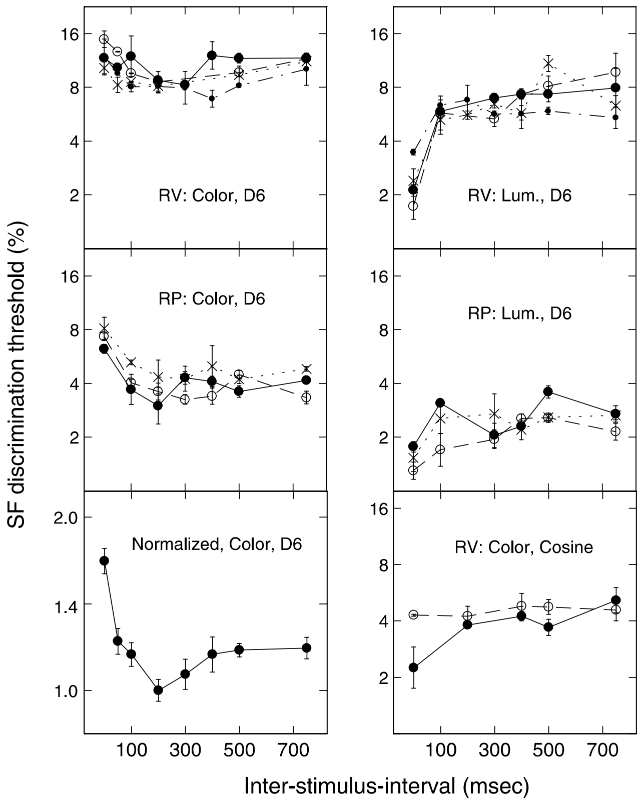

Fig. 2. Foveal, photopic, spatial frequency (SF) discrimination threshold (100 × $\Delta f/f$: in percent) is plotted as a function of the inter-stimulus-interval (in ms). *Top-left panel*: color D6 pattern for observer RV at 1.7 cpd (open circles joined by dashed lines), 2.4 cpd (filled circles joined by solid lines), 3.4 cpd (× joined by dotted lines), and 4.8 cpd (smaller size filled circles joined by dash-dotted lines). *Top-right panel*: luminance D6 for RV at 1.2 cpd (open circles joined by dashed lines), 1.7 cpd (filled circles joined by solid lines), 2.4 cpd (× joined by dotted lines), and 4.8 cpd (smaller size filled circles joined by dash-dotted lines). *Middle-left panel*: color D6 pattern for RP at 2.4 cpd (open circles joined by dashed lines), 2.8 cpd (filled circles joined by solid lines), and 4.8 cpd (× joined by dotted lines). *Middle-right panel*: luminance D6 for RP at 0.5 cpd (open circles joined by dashed lines), 1 cpd (filled circles joined by solid lines), and 1.4 cpd (× joined by dotted lines). *Bottom-left panel*: SF discrimination data normalized with respect to the minimum of the data that were averaged over the normalized data shown in top- and middle-left panels. *Bottom-right panel*: color cosine grating for RV at 0.7 cpd (open circles joined by dashed lines) and 2 cpd (filled circles joined by solid lines). Error bars show ±1 SE.

3.2. SF discriminations versus inter-stimulus-interval curves

To estimate percent SF discrimination the best fit to five SF discrimination data points in a session was obtained using $p = 1-2^{-R}$ where $R = (f/f_0)^q$, p is proportion of correct response, f is SF (cpd), f_0 is SF for $p = 0.5$, and q is an exponent. Corrections were made, as needed, for false alarm and the point of subjective equivalence. In some cases, corrections were needed even in 2IFC method because SF discrimination thresholds (Δf) could be at either side of $p = 0.5$, and f_0 was not always equal to the standard SF. Thresholds (Δf) at $p = 0.25$ and $p = 0.75$ were calculated and averaged. Percent SF discrimination threshold ($100 \times \Delta f/f$) was then calculated.

Percent SF discrimination threshold as a function of inter-stimulus-interval (ISI) are plotted in Fig. 2. Curves in top-left (RV) and middle-left (RP) panels are for D6 color stimuli. Curves in top-right (RV) and middle-right (RP) panels are for D6 luminance stimuli. To investigate the trend in curves, we performed a three-way ANOVA on the data normalized with respect to the minimum for each curve. The three factors were ISI, subject, and SF. For D6 color stimuli (shown in top- and middle-left panels), we found: (a) a significant ISI-effect at $\alpha < 0.01$ [$F = 13.6 > F(7,\ 169,\ 0.01) = 2.75$]; (b) no significant subject-effect (for normalized data) even at $\alpha = 0.05$ [$F = 0.94 < F(1,\ 169,\ 0.05) = 3.9$]; (c) no significant SF-effect (for normalized data) at $\alpha = 0.01$ [$F = 3.41 < F(4,\ 169,\ 0.01) = 3.43$]. [It should be noted that a subject-effect ($F = 372$) and SF-effect ($F = 40.5$) were found on raw (un-normalized) data.] Since there is no significant subject- and SF-effect on these normalized data, we first averaged the normalized data (over subjects and SFs) and then normalized again for the curves shown in top- and middle-left panels to observe the trend. This normalized curve is plotted in the bottom-left panel, and reveals that SF discrimination thresholds have a minimum at about 200 ms. It also shows that SF discrimination is better for color-defined form (500 ms ISI) than that for color apparent-motion task (ISI = 0 ms). The bottom-right panel shows control data using cosine color gratings for observer RV (open circles for 0.7 cpd and filled circles for 2 cpd color gratings). Results are not the same as that for D6 (bottom-left panel); the comparison between D6 and cosine grating is detailed in Section 3.6.

For D6 luminance stimuli (shown in top- and middle-right panels), we found a significant effect at $\alpha < 0.01$ for all three factors even in the normalized data: (a) ISI-effect with $F(6,109) = 12.8 > F(6,\ 109, 0.01) = 2.98$; (b) subject-effect with $F(6,109) = 80.2$; and (c) SF-effect with $F(6,109) = 25.1$. Thus, it is interesting that there is significant individual variation in SF discrimination task, similar to CSFs (detection task) of Fig. 1. The data in top-right and middle-right panels clearly show that SF discrimination for luminance apparent-motion task (0 ms ISI) is better than luminance-defined form (500 ms ISI). This is consistent with the general notion that motion is superior in discriminating and detecting luminance stimuli (Regan, 2000) when stimuli are equated in multiples of threshold. However, Stromeyer, Kronauer, Ryu, Chaparro and Eskew (1995) have made extensive measurement on chromatic/luminance input to motion detection, and for low temporal frequencies the motion system is more sensitive to chromatic than to luminance variations when the stimuli are equated in RMS contrast. We have not equated to RMS contrast so we cannot compare this way. [One could argue that it is more relevant to equate in terms of detection threshold.] Our color stimuli had RMS contrast about one-third of the RMS contrast of luminance stimuli. This comparison also depends on spatial and temporal parameters. However, we can compare the SF discrimination inferred from luminance apparent-motion (*criterion-B*) with that from luminance-defined form (*criterion-A*) at 75% RMS luminance contrast. We find the luminance apparent-motion inferred SF discrimination is indeed superior to luminance-defined form inferred SF discrimination (ISI = 0 versus 500 ms in top- and middle-right panels).

In general, chromatic SF discrimination is best at about 200 ms ISI whereas luminance SF discrimination is best at 0 ms ISI.

3.3. SF discriminations versus duration

We performed a control experiment to measure SF discrimination as a function of stimulus duration at inter-stimulus-interval (ISI) of 500 ms with observer RV. SF discrimination as a function of stimulus duration is plotted in the upper graph of Fig. 3 for color stimuli and in the lower graph for luminance stimuli. Multiple *t*-tests (Vimal, 1998b, 2000) at $\alpha = 0.05$ level yield the following *t* values: (a) For 0.7 cpd, $t(100 \text{ versus } 500 \text{ ms, color}) = 3.95 > t(\mathrm{d}f = 8,\ \alpha_{\mathrm{adj}} = 0.02) = 2.9$ and $t(200 \text{ versus } 500, \text{color}) = 1.1 < t(8, 0.02) = 2.9$, i.e., not significant. That is, the plateau reaches at 200-ms duration because the discrimination threshold for 200 ms is statistically identical (at $\alpha = 0.05$ level) to that for 500 ms for 0.7 cpd color stimuli. (b) For 1.7 cpd, $t(100 \text{ versus } 500, \text{color}) = 2.47 < t(9, 0.02) = 2.82$, but $t(200 \text{ versus } 500, \text{color}) = 3.13 > t(9, 0.02) = 2.82$. That is, the plateau reaches at greater than 200 ms for 1.7 cpd color stimuli. (c) For 1 and 9.5 cpd in lower panel, $t(67 \text{ versus } 500, \text{luminance}) = 0.2\ \&\ 2.15$, which is not significant at $\alpha_{\mathrm{adj}} = 0.01$ level except for 4 cpd D6: $t(67 \text{ versus } 500, \text{luminance}) = 3.21 > t(18, 0.01) = 2.88$. That is, the plateau reaches at or greater than 67 ms for luminance stimuli.

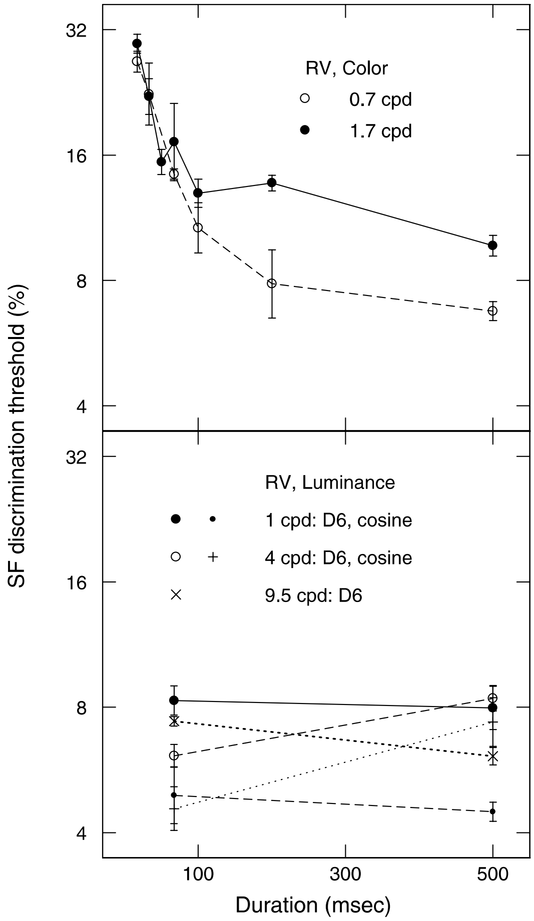

Fig. 3. SF discrimination threshold is plotted as a function of stimulus duration (in ms) with ISI = 500 ms for observer RV (control experiment). *Upper graph*: Color D6 pattern at 0.7 cpd (open circles joined by dashed lines) and 1.7 cpd (filled circles joined by solid lines). *Lower graph*: luminance patterns at 1 cpd (large filled circles joined by solid line for D6, small filled circles joined by dashed line for cosine), 4 cpd (open circles joined by dashed line for D6, + joined by dotted line for cosine), 9.5 cpd (× joined by bold dotted line for D6). The duration to reach plateau is smaller for the luminance patterns than that for the color patterns.

Thus, in general, the duration for reaching plateau is smaller for luminance stimuli (equal to or greater than 67-ms) than that for color stimuli (equal to or greater than 200-ms).

3.4. Comparison of SF discriminations for two criteria (500 ms ISI versus 0 ms ISI)

The ISI study described in Section 3.2 was extended to a larger set of SFs for further investigation. SF discriminations as function of SF are plotted in the left panels of Fig. 4 for color stimuli and in the right panels for luminance stimuli. Upper panels are for observer RV and lower panels for RP. Filled circles represent data with *criterion-A* (size/SF, 500 ms ISI) and open circles with *criterion-B* (apparent motion, 0 ms ISI); for these data, the temporal presentation was Gaussian.

For color stimuli, SF discrimination with size/SF *criterion-A* is largely better than that with apparent motion *criterion-B*. This is supported by two-way ANOVA with SF and ISI as factors. We found both (a) SF-effect [$F = 4.49 > F(15, 111, 0.01) = 2.21$ for RV in top-left panel of Fig. 4; $F = 10 > F(14, 139, 0.01) = 2.22$ for RP in bottom-left panel] and (b) ISI-effect [$F = 24.2 > F(1, 111, 0.01) = 6.89$ for RV; $F = 133.6 > F(1, 139,\ 0.01) = 6.83$ for RP] at $\alpha = 0.01$ significance level.

On the other hand, for luminance stimuli, in general, SF discrimination with apparent motion criterion is better than that with size/SF criterion (except at few data points at higher SFs for RP, as shown in lower right panel of Fig. 4). This is supported by two-way ANOVA with SF and ISI as factors; we found both: (a) SF-effect [$F = 4.15 > F(17, 102, 0.01) = 2.18$ for RV in top-right panel; $F = 4.61 > F(11, 76, 0.01) = 2.5$ for RP in bottom-right panel] and (b) ISI-effect [$F = 190.6 > F(1, 102, 0.01) = 6.9$ for RV; $F = 17 > F(1, 76, 0.01) = 6.99$ for RP] at $\alpha = 0.01$ significance level.

Furthermore, under SF/size criterion, chromatic SF discrimination with 8 Hz sinusoidal presentation is largely similar to that with Gaussian presentation (as shown in top left panel of Fig. 4: × joined by dotted line versus filled circles joined by solid lines). This is validated by two-way ANOVA with SF and temporal presentation as factors; we found SF-effect [$F = 9.9 > F(13, 77, 0.01) = 2.37$] but no temporal presentation effect [$F = 0.29 < F(1, 77, 0.05) = 6.98$].

In general, SF discrimination for luminance apparent-motion task is better than that for luminance-

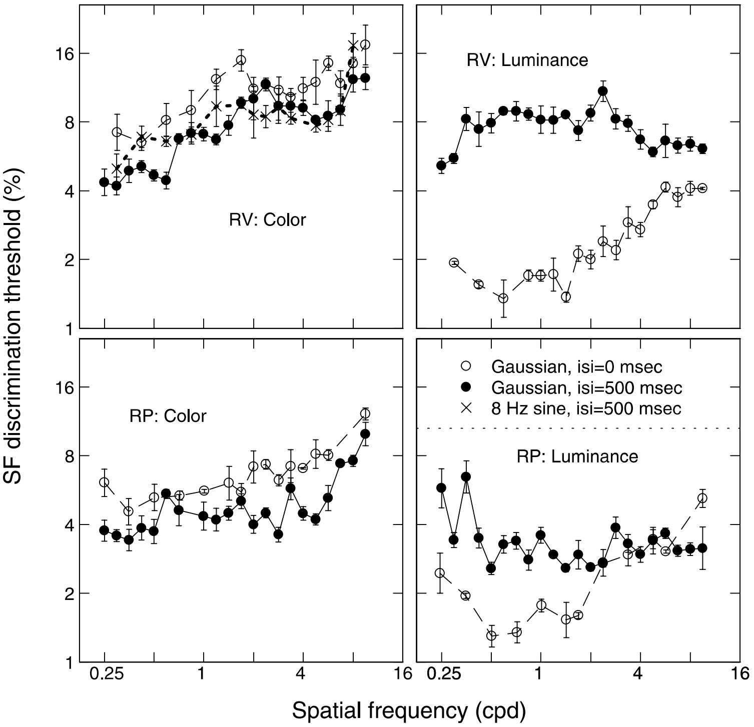

Fig. 4. SF discrimination threshold is plotted as a function of the SF of a D6 pattern. The duration of the stimulus was 500 ms. Filled circles joined by solid lines: Gaussian presentation with inter-stimulus-interval (ISI) = 500 ms, using SF/size criterion. Open circles joined by dashed lines: Gaussian presentation with ISI = 0 ms using apparent motion (contraction/expansion) criterion. × joined by dotted lines: 8 Hz sinusoidal presentation with ISI = 500 ms. Error bars show ±1 SE. *Top-left panel*: observer RV with color stimuli. *Top-right panel*: RV with luminance stimuli. *Bottom-left panel*: RP with color stimuli. *Bottom-right panel*: RP with luminance stimuli.

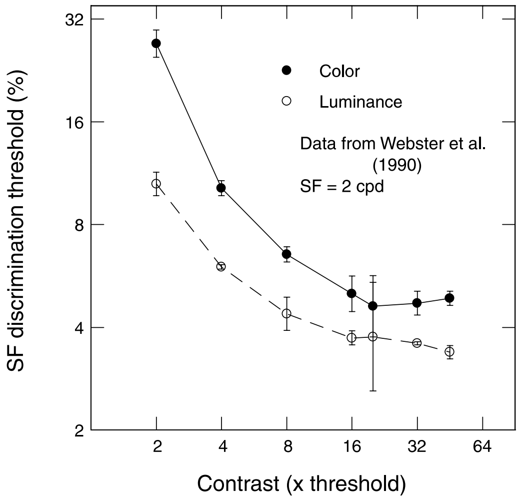

Fig. 5. SF discrimination threshold is plotted as a function of contrast (in times threshold units). The curves are plotted by averaging the data over two subjects shown in Fig. 5 (and Fig. 7 for 20×) of Webster et al. (1990) for SF = 2 cpd. The curve with filled circles joined by solid lines represents their averaged data for color (L–M) stimuli and that with open circles joined by dashed lines for luminance stimuli.

defined form whereas the SF discrimination is worse for chromatic apparent-motion task than that for color-defined form.

3.5. Comparison of chromatic and achromatic SF discriminations

3.5.1. SF discrimination versus contrast

In order to compare chromatic data with luminance data, we must have some common metric. We selected the same contrast in *times* threshold as a basis for comparison; this basis was also used by Webster et al. (1990). For this purpose, we need SF discrimination data as a function of contrast in *times* threshold units. Unfortunately, we did not measure this data, however, similar data were reported in Fig. 5 (and Fig. 7 for 20×) of Webster et al. (1990) for SF of 2 cpd. We therefore averaged the data of their two subjects and plotted in Fig. 5 (for the benefit of readers), which along with CSFs of Fig. 1 was used for estimating SF discrimination at 8×-threshold contrast for color and luminance stimuli. We used an interpolation technique to estimate SF discrimination for 8×-threshold contrast on octave–octave units. The resulted SF discriminations as a function of SF are plotted in Fig. 6, where the data for RV and RP are re-plotted from Fig. 4 using this *estimation* procedure.

Thus, in Fig. 6 (except the right-bottom panel of Fig. 6a), the data are *estimated* SF discriminations at 8×-threshold contrast. This method of estimation rests on

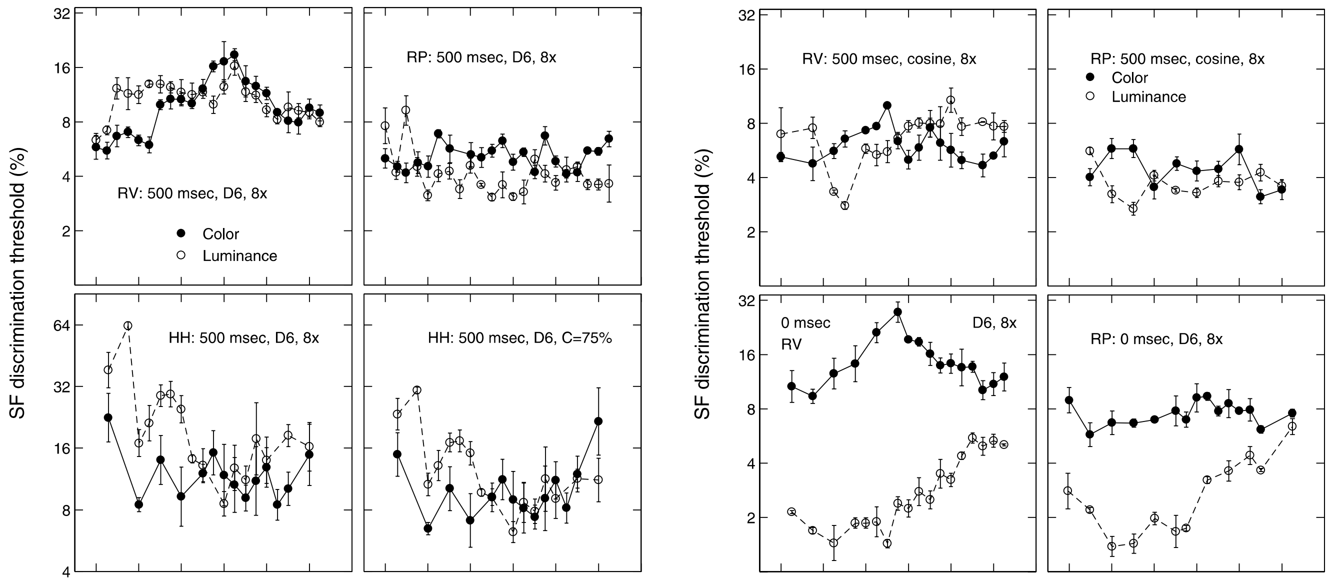

Fig. 6. Comparison of SF discrimination thresholds for color and luminance stimuli as a function of the SF. The curve with filled circles joined by solid lines represents data for color stimuli and that with open circles joined by dashed lines for luminance stimuli. Error bars show ±1 SE. (a) *Top-left panel*: observer RV with D6 stimuli at contrast of 8×-threshold contrast with ISI = 500 ms. *Top-right panel*: RP with D6 stimuli, contrast = 8×, ISI = 500 ms. *Bottom-left panel*: HH with D6 stimuli, contrast = 8×, ISI = 500 ms (based on estimated contrast thresholds). *Bottom-right panel*: HH with D6 stimuli, 75% stimulus contrast, ISI = 500 ms. (b) *Top-left panel*: RV with cosine stimuli at 8× threshold contrast and ISI = 500 ms. *Top-right panel*: RP with cosine stimuli, contrast = 8×, ISI = 500 ms. *Bottom-left panel*: RV with D6 stimuli, contrast = 8×, ISI = 0 ms. *Bottom-right panel*: RP with D6 stimuli, contrast = 8×, ISI = 0 ms. An interpolation technique was used to estimate SF discrimination for 8×-threshold contrast: For a specific SF with SF discrimination of sfd1 (Fig. 4), contrast sensitivity was estimated from CSF, which was multiplied by 0.75 (stimulus contrast of 75%) to obtain the times threshold contrast (*n*×). The SF discrimination at 8× for a subject = sfd1 × sfd2/sfd3, where sfd2 and sfd3 are the SF discriminations at 8× and at *n*×, respectively, estimated from Fig. 5.

the assumption that the curves in Fig. 5 are more or less similar for all SFs and for all subjects. Further investigation is necessary to verify this. In general, the trend in SF discrimination as a function of SF did not change before and after the application of Fig. 5, and shows that while color appears to perform better than luminance vision at low SFs, this effect is lost or even reversed at high SFs. For example, compare the bottom-left panel for 8×-threshold contrast versus the bottom-right panel for 75% stimulus contrast for subject HH. This trend was also true for RV and RP (not plotted for brevity). Thus, this general conclusion is not dependent on the above assumption.

3.5.2. Comparison of chromatic and achromatic SF discriminations with SF/size criterion

In *criterion-A* (ISI of 500 ms), SF discriminations were based on SF and/or size. SF discrimination thresholds as a function of the SF are plotted in Fig. 6a, b: (i) top-left panel of Fig. 6a is for observer RV at 8×-threshold contrast with D6 pattern; (ii) top-right panel of Fig. 6a is for RP (8×, D6); (iii) bottom-left panel of Fig. 6a is for HH (8×, D6); (iv) bottom-right panel of Fig. 6a is for HH at 75% stimulus contrast (raw data, D6); (v) top-left panel of Fig. 6b is for RV with cosine pattern at 8×; (vi) top-right panel of Fig. 6b is for RP with cosine pattern at 8×. Open circles joined by dashed lines show in phase (achromatic) data and filled circles joined by solid lines antiphase (chromatic) data. For the data in each panel, we performed two-way ANOVA with two factors: SF and color-luminance-comparison.

For RV (top-left panel of Fig. 6a), we found a SF-effect [$F = 8.4 > F(21, 153, 0.01) = 2$]. In addition, SF discrimination for color stimuli is better than that for luminance stimuli at SFs 0.25–1.4 cpd [$F = 11.3 > F(1, 70, 0.01) = 7.01$] and largely worse at higher SFs [$F = 6 > F(1, 83, 0.05) = 3.96$].

For RP (top-right panel of Fig. 6a), we found a SF-effect [$F = 6.47 > F(20, 227, 0.01) = 1.97$]; SF discrimination for color stimuli is largely better than that for luminance stimuli at SFs 0.25–0.35 cpd [$F = 7.07 > F(1, 49, 0.05) = 4.04$], and worse at higher SFs [$F = 42.3 > F(1, 178, 0.01) = 6.79$].

For HH (bottom panels of Fig. 6a), a CSF was not measured so we could not estimate his SF discrimination precisely at 8×-threshold contrast. However, we used the CSF data averaged over RV and RP, and plotted the D6 SF discrimination data at 8×-threshold contrast in bottom-left panel and the raw data at 75% stimulus contrast in bottom-right panel. It should be noted that the plot in the bottom-left panel might not be reliable, as CSF data for HH were not available. However, the results are largely similar to those of RV and RP. Data in bottom-left panel yielded a SF-effect [$F = 3.58 > F(11, 70, 0.01) = 2.51$] and color-luminance effect [$F = 15.3 > F(1, 70, 0.01) = 7.01$]; chromatic SF discrimination is better at lower SFs 0.3–1.4 cpd [$F = 8.5 > F(1, 47, 0.01) = 7.2$] and similar at higher SFs [$F = 0.53 < F(1, 23, 0.05) = 4.28$]. This trend is more or less similar to that in the bottom-right panel.

For cosine gratings (Fig. 6b, top panels), compared to luminance stimuli, SF discrimination for color stimuli is: (a) better at low SFs 0.25–0.42 cpd; (b) worse at SFs 0.6–1.4 cpd [$F = 26.8 > F(1, 37, 0.01) = 7.39$] for RV and worse at 0.5–8 cpd [$F = 18.2 > F(1, 165, 0.01) = 6.8$] for RP; and (c) surprisingly better at SFs 1.7–8 cpd [$F = 19.1 > F(1, 51, 0.01) = 7.1$] for RV.

In general, SF discrimination for D6 color stimuli is better than that for luminance stimuli at low SFs, and similar or worse at higher SFs with *criterion-A* for all subjects at 8×-threshold contrast, and 20×-threshold contrast (not plotted).

3.5.3. Comparison of chromatic and achromatic SF discriminations with apparent motion criterion

In *criterion-B*, SF discriminations were based on apparent motion of contraction/expansion. SF discrimination thresholds were plotted as a function of the SF in Fig. 6b (bottom-left panel for RV and bottom-right panel for RP) at 8×-threshold contrast for D6 pattern. For the apparent-motion task, SF discrimination thresholds to achromatic (inphase) stimuli were always lower than the chromatic (antiphase) stimuli for all SFs by a large amount. This conclusion is supported by a two-way ANOVA with two factors: a SF and color-luminance-comparison. SF-effect, with the larger data set, is analyzed in Section 3.4; but here also it is significant [for RV: $F = 3.37 > F(15, 93, 0.01) = 2.23$; for RP: $F = 6.47 > F(20, 227, 0.01) = 1.97$]. For the color-luminance-comparison effect, we found that the SF discrimination for luminance stimuli is significantly better than that for color stimuli with *criterion-B* for all SFs and for both subjects by a large amount [for RV: $F = 189 > F(1, 93, 0.01) = 6.93$; for RP: $F = 223 > F(1, 35, 0.01) = 7.42$].

In general, SF discrimination for luminance stimuli is much better than that for color stimuli at all SFs under the apparent motion *criterion-B*. This validates the assumption that *criterion-B* activated a motion channel. If discriminations were due to SF/size in *criterion-B* as well, then results should have been similar to that obtained for *criterion-A*. The results suggest that color and motion are largely segregated. However, motion was still seen with color stimuli; therefore, color and motion weakly interact, which can be interpreted as a weak chromatic input to separable motion channel via divisive inhibition.

3.6. Comparison of D6 versus cosine SF discriminations

The significance of this comparison is to investigate if there is any pattern-type effect. This is necessary because many investigators (Kelly, 1983; Mullen, 1985; Vimal, 1997, 1998a,b) have used D6 or sinusoidal patterns and found different results for CSFs (higher CSF for sinusoidal patterns). Our interest was to investigate if there is any similar difference for luminance and chromatic SF discriminations.

3.6.1. Color D6 versus cosine patterns

We performed two-way ANOVA with two factors (SF and pattern-type) on our data at 75% stimulus contrast for each subject. We found significant pattern-type effect for RV [$F = 202$ (raw data) and 134 (normalized data with respect to data at 2 cpd) $> F(1, 104, 0.01) = 6.89$] but no effect for RP [$F = 0.97$ (raw data) and 0.32 (normalized data) $< F(1, 128, 0.05) = 6.84$]. The SF discrimination thresholds at 2 cpd were 10.1% (RV, D6), 3.7% (RV, cosine), 4% (RP, D6), and 3.36% (RP, cosine), which were used in the normalization. The three-way ANOVA with three factors (SF, subject, and pattern type) on the normalized data yielded no significant subject-effect [$F = 0.55 < F(2, 232, 0.05) = 3.04$], but significant pattern-type effect [$F = 43.1 > F(2, 232, 0.01) = 4.7$]; on raw data we found significant effects for all three factors: SF [$F = 21 > F(19, 232, 0.01) = 1.68$], subject [$F = 244 > F(1, 232, 0.01) = 6.75$], and pattern-type [$F = 136 > F(1, 232, 0.01) = 6.75$]. In general, there is a pattern-type effect for color stimuli.

3.6.2. Luminance D6 versus cosine patterns

For luminance patterns, two-way ANOVA yielded significant pattern effect for RV on raw data [$F = 36.3 > F(1, 106, 0.01) = 3.94$], but not on normalized data (with respect to data at 2 cpd) [$F(1, 106) = 0.33$]; for RP, there is a significant pattern effect on both raw [$F(1, 156) = 14 > F(1, 156, 0.01) = 6.81$] and normalized data [$F = 23.3$]. The SF discrimination thresholds at 2 cpd were 8.7% (RV, D6), 5.8% (RV, cosine), 2.6% (RP, D6), and 2.7% (RP, cosine) that were used for normalization. [Note for RP at 0.35 cpd, discriminations were 6.5% for D6 and 4.3% for cosine patterns.] The three-way ANOVA with three factors (SF, subject, and pattern type) on the normalized data yielded significant subject-effect [$F = 18.7 > F(1, 164, 0.01) = 6.8$] but no significant pattern-type effect [$F = 2.89$]; on raw data we found significant effects on all three factors: SF [$F = 11 > F(6, 164, 0.01) = 2.92$], subject [$F = 332 > F(1, 164, 0.01) = 6.8$], and pattern-type [$F = 57 > F(1, 164, 0.01) = 6.8$]. In general, there is a pattern-type effect on raw data for luminance stimuli.

Thus, pattern-type effect was found on raw data for both color and luminance stimuli. In general, SF discrimination for cosine (spatially not localized) grating is better than that for D6 (localized) patterns (top panels of Fig. 6b for cosine versus top panels of Fig. 6a for D6). This is consistent with higher contrast sensitivity of cosine grating than that of localized D6 pattern. In addition, viewing angle for cosine grating test (4° circular) was larger than that for D6 (2°–4° × 0.5°, Section 2.4), which might have led to better SF discrimination with cosine grating. We performed a control experiment to measure contrast sensitivities with these viewing angles using D6 patterns and found that 4° circular D6 color test on dark surround had higher sensitivity than 2°–4° × 0.5° D6 on 6.4° equiluminant background.

4. Discussion

Since stimulus-contrast of 75% was significantly above threshold contrasts (highest threshold contrast in Fig. 1 was 19% at 9.5 cpd for RP), both types (criteria A and B) of SF discrimination experiments were suprathreshold experiments. The color and luminance CSFs (Fig. 1) are consistent with previous studies (Kelly, 1983; Mullen, 1985; Vimal, 1998a,b, 2000, 2002). SF discrimination data can be explained by the relative activities (slopes) of the SF tuned mechanisms (Wilson & Gelb, 1984; Regan, 2000) that are responsive to: (a) color-defined form; (b) luminance-defined form; (c) luminance apparent-motion task; and (d) chromatic apparent-motion task. In addition, SF discrimination can be considered similar to hyperacuity task because Δf is significantly less than the bandwidths of CSFs and SF tuned mechanisms (Wilson et al., 1983; Wilson & Gelb, 1984; Wilson, 1986; Vimal, 1998a; Regan, 2000). A reason for considering SF discrimination as a hyperacuity task is that hyperacuity can be explained by the relative activities between SF tuned mechanisms (see Wilson, 1986), as is also used to explain SF discrimination (see Wilson & Gelb, 1984; Regan, 2000). Furthermore, Δf is significantly less than the spatial bandwidths, as shown by our statistical analysis: SF discrimination thresholds Δf ranged 0.036–0.91 octaves; mean $\Delta f \pm \mathrm{SE}$ was 0.21 ± 0.009 octaves ($n = 115$) for color, 0.16 ± 0.012 octaves ($n = 117$) for luminance, and 0.19 ± 0.008 ($n = 232$) for both combined. The full bandwidths of SF tuned chromatic mechanisms ranged 0.5–4.4 octaves (Losada & Mullen, 1994: 2.1–4.3 octaves; Losada & Mullen, 1995: 1.0–1.61 octaves; Vimal: 1.0–4.4 octaves; Mullen & Losada, 1999: 0.5–0.86, foveal); mean ± SE was 2.19 ± 0.19 octaves ($n = 28$). The full bandwidths of SF tuned luminance mechanisms ranged 0.7–2.9 octaves (Wilson et al., 1983: 1.27–2.5; Losada & Mullen, 1994: 1.6–2.9 octaves, Losada & Mullen, 1995: 1.22–1.36 octaves; Mullen & Losada: 0.7–0.72, foveal); mean ± SE was 1.59 ± 0.13 octaves ($n = 18$). The full bandwidth of both color and luminance mechanisms combined was mean ± SE = 1.96 ± 0.13 octaves ($n = 46$). For both color and luminance combined, $t = 29.5 \gg t(276, 0.001) = 3.36$, indicating SF discrimination thresholds are significantly lower than bandwidths of SF tuned mechanisms, on average about one-tenth of the full bandwidth. Thus, in these terms, SF discrimination could be considered as a hyperacuity task.

4.1. SF discriminations versus inter-stimulus-interval

As described in Section 3.1 and plotted in Fig. 2 (bottom-left panel), chromatic SF discrimination with SF/size criterion (500 ms) is: (a) better than that with apparent motion criterion (0 ms); and (b) best at about 200 ms ISI. This suggests that the relative activities of chromatic SF tuned mechanisms may be higher for color-defined form than that for chromatic apparent-motion task. If both (form and apparent motion) are present, relative activities of mechanisms cooperatively lead to better SF discrimination for color. On the other hand, since luminance SF discrimination is best at 0 ms ISI, the relative activities of luminance SF tuned mechanisms may be much higher for luminance apparent-motion task than that for luminance-defined form. In addition, if the attributes of the latter are mixed with that of the former (that causes apparent-motion contrast to decrease), relative activities of mechanisms responsive to motion may degrade leading to worsening of SF discrimination. One could also argue that luminance SF discrimination gets better when apparent motion is mixed to luminance-defined form, meaning when ISI decreases from 500 ms.

Furthermore, 500-ms versus 0-ms ISI study was extended to larger data set (0.25–9.5 cpd) and confirmed the above findings as shown in Fig. 4 and Section 3.4. SF discrimination with color-defined form (500-ms data) is largely better than that with chromatic apparent-motion task (0-ms data). On the other hand, in general, SF discrimination with luminance apparent-motion task is better than that with luminance-defined form.

Furthermore, color-defined SF discrimination with transient (8 Hz sinusoidal) presentation is largely similar to that with sustained (Gaussian) presentation. This is consistent with following hypothesis: The 8 Hz pattern was a red–green spatially D6 but temporally it was modulated sinusoidally on equiluminant yellow background: the central red bar temporally fluctuated between red and yellow, whilst the adjacent flanking bars fluctuated between yellow and green. It can be considered equivalent to a stationary red–green patch plus a counterphase flickering red–green patch of equivalent contrast presented in phase. Similar achromatic on–off gratings were used by Kulokowski and Tolhurst (1973). Sensitivity to stationary component may be higher than the counterphase flicker component (Vimal, Pandey, & McCagg, 1995), making 8 Hz pattern approximately equivalent to Gaussian pattern and hence both have largely similar SF discrimination.

4.2. SF discriminations versus duration

In general, the duration of the temporal integration for SF discrimination (the duration for reaching plateau) is smaller with luminance stimuli ($\geqslant$ 67-ms) than that with color stimuli ($\geqslant$ 200-ms). In other words, the temporal integration of the relative activities of SF tuned mechanisms was longer for color-defined form than that for luminance-defined form. This trend is consistent with a temporal integration study (Smith, Bowen, & Pokorny, 1984), although magnitudes are different because of different tasks. Smith et al. measured colorimetric purity and increment thresholds both as a function of duration. They reported that the duration of temporal integration was lower for 'white' stimuli (about 160 ms) than that for chromatic stimuli (about 640 ms). In general, our data is also consistent with shorter time course for luminance than for color (Burr & Morrone, 1993; Cropper & Derrington, 1993; Metha & Mullen, 1996, 1997).

4.3. Comparison of chromatic and achromatic SF discriminations

In order to compare chromatic data with luminance data, we must have some common basis. We selected the eight times threshold contrast (8×) as a basis for comparison because at high SF such as 8 cpd, color contrast sensitivity is about 6, although at 20× results are mostly similar. SF discriminations at 8× were estimated using the discrimination data collected at 75% stimulus contrast and Fig. 1 (CSFs) and Fig. 5 (SF discrimination versus contrast: derived from Webster et al., 1990). The SF discrimination thresholds as a function of SF are plotted in Fig. 6a, b.

For SF discriminations based on SF and/or size (*criterion-A*), chromatic SF discrimination is better than achromatic at low SFs, and similar or worse at higher SFs. This suggests that the relative activities of SF tuned mechanisms responsive to color-defined form may be greater than that for luminance-defined form at low SFs, and similar or smaller at higher SFs. This rejects the notion of color vision being deficient for all SF discriminations (Webster et al., 1990). The data of observer RP (top-right panel of Fig. 6) are consistent with Webster et al. (1990) who reported that chromatic SF discrimination is better for luminance stimuli for SFs 0.5–4 cpd for their subject MW (their Fig. 7: only four data point pairs). It is not clear that this was true for their second subject (AL: two out of four data point pairs appear similar) because a statistical analysis was not reported.

For SF discriminations based on apparent motion of contraction/expansion (*criterion-B*), SF discrimination for color stimuli is much worse than that for luminance stimuli at all SFs. This suggests that the relative activities within a population of SF tuned mechanisms responsive to chromatic apparent-motion task are significantly lower than those responsive to luminance apparent-motion task. Furthermore, this is consistent with the notion that color and motion channels are largely segregated at threshold (Livingstone & Hubel, 1987); this is similar to the finding that at detection threshold color and luminance mechanisms are stochastically independent (Mullen & Sankeralli, 1999). However, apparent motion was still seen for color stimuli (because that was the criterion), this means color and motion weakly interact, consistent with Cavanagh and Favreau (1985). One could also argue that there might be a separate chromatic motion mechanism (see below). Our data is unable to differentiate between these two hypotheses.

Stromeyer et al. (1995) reported that a red–green hue mechanism may mediate chromatic detection, and a separate spectrally opponent motion mechanism may mediate motion. The phase-shift between L and M cone signals within the two motion mechanisms may imply that moving chromatic gratings, when suprathreshold, will directly stimulate the luminance mechanism.

Baker, Boulton, and Mullen (1998) reported that small temporal intervals between frames might activate quasi-linear (first order) motion mechanisms and large intervals nonlinear motion mechanisms. Chromatic linear motion may be solely based on a luminance signal (unaffected by color noise) and the nonlinear chromatic motion mechanism may be purely chromatic (unaffected by luminance noise) (Yoshizawa, Mullen, & Baker, 2000). In addition, the response of the quasi-linear mechanism is severely impaired for color stimuli, while the nonlinear mechanism remains fully operative. Furthermore, suprathreshold color mechanisms can interact with luminance mechanisms via divisive inhibition (Vimal 1998b; Chen, Foley, & Brainard, 2000). One could argue that it is not surprising that color performs worse in apparent motion task. Apparent motion for chromatic stimuli is controversial and may be weak or absent for chromatic stimuli under first order conditions. Even when found, it may be based on luminance artifacts. However, we have minimized luminance artifacts (Sections 2.1, 2.3 and 2.4). Thus, the above findings may imply that SF discrimination (suprathreshold task) inferred from 'form defined expansive/contractive apparent-motion' at zero ISI might involve chromatic motion mechanism, luminance motion mechanism, and/or weak interaction between color and motion mechanisms.

As described in Section 3.6, a pattern-type (D6 versus cosine) effect and subject effect were found on raw data for both color and luminance stimuli but the consistent effects were not obtained on normalized data. The pattern-type effect may be due to: (a) larger viewing angle for cosine grating; and (b) D6 being a localized stimulus. Furthermore, there is subject-effect on raw data and to some extent on the normalized SF discrimination data of RV, RP, and HH. This subject effect is not inconsistent with individual variation found in CSFs (Fig. 1, Mullen, 1985; Vimal, 1998a,b, 2000, 2002). In other words, if there is well known individual variation in detection thresholds, there is no good reason why the individual variation should not be present in SF discrimination at suprathreshold levels. However, as expected, there are some findings that are common among all subjects and pattern-types. For example, SF discrimination is: (i) better at low SFs for color-defined form than that for luminance-defined form; (ii) better at all SFs for luminance apparent-motion task than that for luminance form, color form, and chromatic apparent-motion task; and (iii) best at about 200 ms for color stimuli; (iv) in addition, SF discrimination gets better with increasing duration and contrast until it reaches plateau.

The controversy (Section 1) that color vision is deficient in form perception needs to be clarified. We conclude that the comparative performance of color and luminance vision depends on the task and spatiotemporal characteristics of stimuli according to the results of this paper. For example, compared to luminance vision, color vision is indeed better at low SF discrimination, and equal to or worse at higher SFs. Both color and luminance vision were equally good on contour integration over a wide range of curvatures (Mullen et al., 2000). The current paper is consistent with the idea that color and form are not segregated rather they interact under some conditions.

4.4. Possible models

Achromatic photopic SF discrimination data have been explained by spatial line-element model (Wilson & Gelb, 1984; Wilson & Regan, 1984) using the concept of relative activities (slopes) of SF tuned mechanisms (Wilson et al., 1983) and also by opponent model (Regan, 1985, 1989, 2000; Regan & Beverley, 1983, 1985). These models use SF-tuned mechanisms derived from masking model that is mostly based on feed-forward excitation, where no divisive inhibition was included in the extraction of SF-tuned mechanisms. However, recent data suggest that divisive inhibition is involved in the processing of spatial information for luminance, color, and their interaction (Foley, 1994; Chen et al., 2000). Therefore, divisive inhibition should be included in the extraction of the SF tuned mechanisms (Wilson et al., 1983; Vimal, 1998a). This information is not yet available for the extraction of SF tuned mechanisms of both achromatic and chromatic channels and hence the modeling for the SF discrimination data is beyond the scope of this paper. Qualitatively, one could also argue that SF discrimination for chromatic apparent-motion task might be explained by the relative activities of luminance SF tuned mechanisms responsive to luminance apparent-motion task via divisive inhibition of luminance mechanisms by color mechanisms.

4.5. Physiological interpretation

The *parvo-interblob* system (Livingstone & Hubel, 1987) appears to be sensitive to both achromatic and chromatic contrasts; this system may be responsible for the processing of color-defined form discrimination. The achromatic channel might include both *magno* system (Livingstone & Hubel, 1987) and the achromatic component of the *parvo-interblob* system, which may be responsible for luminance-defined SF discrimination. SF discrimination for luminance apparent-motion task may be due to the relative activities of achromatic SF tuned mechanisms of magno-MT pathway responsive to motion. The high SF discrimination thresholds for chromatic apparent-motion task may be due to chromatic contrast component of *parvo-interblob* system responsive to chromatic motion, or may be due to magno-MT pathway via divisive inhibition by color system.

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