

Changes in Contrast Thresholds with Mean Luminance for Chromatic and Luminance Gratings: A Reexamination of the Transition from the DeVries–Rose to Weber Regions[†]

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We have examined the influence of the mean luminance level on the detection thresholds for luminance and red–green chromatic gratings for three different spatial frequencies. The changes in detection thresholds according to the mean luminance level reflect the two different regions, the DeVries–Rose and Weber ranges, found in previous studies. The results for luminance gratings suggest that the transition luminance is proportional to the spatial frequency of the grating. Predictions based on the constant-flux hypothesis indicate, however, that the transition luminance is proportional to the square of the spatial frequency of the grating and so do not describe the distributions of luminance contrast thresholds adequately. For chromatic gratings, we obtained the same transition luminance for the two lowest spatial frequencies, showing that luminance and chromatic mechanisms behave differently as far as the dependence of the transition luminance on spatial frequency is concerned. Our results suggest that the transition luminance is related to the peak spatial frequency of visual mechanisms that respond to luminance and chromatic gratings. © 2004 Wiley Periodicals, Inc. Col Res Appl, 29, 177–182, 2004; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.20003

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INTRODUCTION

There are numerous descriptions in the literature of so-called *parametric experiments* in the field of spatial vision. In these studies the authors analyze the influence of such experimental parameters as mean luminance level,^{1–3} orientation,^{2,4} spatial position,⁵ spatial extent,^{6,7} and temporal extent⁸ on the sensitivity thresholds for sinusoidal luminance gratings. Any variation in these parameters may change sensitivity thresholds, with the best performance resulting for a given range of spatiotemporal parameter values.

Luminance level is one of the key parameters affecting the detection thresholds of sinusoidal gratings. At low mean luminance levels the contrast thresholds inversely are proportional to the square root of the mean luminance,⁹ according to the following expression:

$$C \propto L^{-1/2}, \quad (1)$$

where C is the contrast threshold and L is the mean luminance of the grating. This relationship is referred to as the DeVries–Rose law and was proposed by Van Nes and Bouman for stationary gratings.¹⁰ At high mean luminance levels the contrast threshold obeys the Weber relationship when a certain mean luminance level is reached as follows:

$$C = k, \quad (2)$$

where k is a constant value. In this region the differential luminance threshold, ΔL , is proportional to the mean luminance of the stimulus. The mean luminance at which a

contrast threshold moves from the DeVries–Rose range to the Weber range has been reported to be proportional to the square of the spatial frequency of the grating.³ This behavior is usually explained by the so-called *constant-flux* hypothesis, which assumes that the flux (the sum of the mean luminance throughout the area of the excitatory center of the mechanism or cell, which is proportional to the inverse square of the preferred spatial frequency of the cell) determines the transition luminance.¹⁰ For the threshold to arrive at the stationary region the flux must reach a certain minimum value, which remains constant for the different spatial frequencies (hence the name of the hypothesis). Thus the higher the spatial frequency, the greater the extension of the DeVries–Rose region for a given range of mean luminance values covering both regions.

Few studies have been made with chromatic rather than luminance gratings and most of these focus mainly on contrast sensitivity changes versus spatial frequency, neglecting other parametric issues.^{11–13} There is therefore a lack of reliable data to address questions about how the influence of the mean luminance level may differ between luminance and red–green chromatic gratings and the whole subject requires further examination. Van der Horst and Bouman,¹¹ who measured chromatic-contrast sensitivity thresholds for different retinal illuminances, found that the DeVries–Rose law described their results adequately, but as their luminance variation range was restricted to quite low levels (before the Weber law behavior was reached) they did not question the validity of the constant-flux hypothesis. More recently Sekiguchi *et al.*¹⁴ have reported that foveal isoluminance contrast sensitivity is a function of retinal illuminance. For red–green gratings of 10 cycles per degree (cpd) their results show points beyond the validity range of the DeVries–Rose law (around 1000 troland). The few points shown (see Fig. 5 in Ref. 14) are insufficient to lead to any firm conclusions. Nor did these authors study transition luminance or its dependence on spatial frequency.

We provide in this report data for sinusoidal chromatic and luminance gratings of three spatial frequencies (0.5, 1.0, and 2.0 cpd). We used a two-alternative, forced-choice method to measure the detection thresholds for both kinds of gratings with different mean luminance levels. The influence of the mean luminance of the gratings on contrast threshold values is analyzed, and the predictions of the constant-flux hypothesis are tested.

METHODS

Stimuli

The stimuli were horizontal, stationary, isoluminant, red–green chromatic gratings, and luminance gratings with a raised-cosine envelope along the axis of modulation to avoid sharp border effects. The overall phase of the stimulus was fixed at 0°. We defined the chromatic contrast of the gratings as follows:

$$C_{r-g} = \frac{RG_1 - RG_2}{K_{r-g}}, \quad (3)$$

where RG_1 and RG_2 are the excitations of the red–green chromatic channel¹⁵ for the two colors between which the chromaticity is modulated to generate the grating (calculated as $L - 2M$, where L and M are cone-excitation values), and K_{r-g} is a constant value calculated to make the maximum contrast value of unity.¹⁶ This value, which was conditioned by the limits of our experimental device in the generation of color gratings, was fixed at 7.52 cd/m². The chromaticities of the red and the green stimuli were ($x_r = 0.409$, $y_r = 0.295$, $x_g = 0.237$, $y_g = 0.382$) at maximum contrast. The contrast arrived at its minimum value of zero when both colors were the same and their chromaticity coordinates were those of an equienergy stimulus (i.e., a stimulus characterized by a flat spectral power distribution or any of its metamers). Isoluminance for each pair of colors was evaluated with standard heterochromatic flicker photometry (HFP) using an equienergy stimulus with a luminance of 21.50 cd/m² as the reference white. The flicker frequency was fixed at 20 Hz and the field size was the same as that used in the threshold determinations. Isoluminance was measured for six different contrast values and there was no significant difference in the settings throughout the mean luminances used in the experiment.

For the chromatic gratings 13 different mean luminance values were chosen, ranging from 0.5 to 77 cd/m². The lowest values were obtained by using two neutral density filters (B+W ND of 0.9 and 1.8 density, manufactured by Schneider Kreuznach GmbH). The minimum value of 0.5 cd/m² is above the stabilization luminance for HFP settings¹⁷ (about 1 td) and just above the saturation threshold for rods¹⁸ (about 1 log td).

For luminance gratings the contrast was calculated by using the standard Michelson contrast as follows:

$$C_L = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}. \quad (4)$$

Six different values of mean luminance, ranging from 0.42 to 82.50 cd/m², were selected. Thus about half the luminance values for the luminance gratings and more than half for the chromatic gratings were within the photopic range, which, according to CIE recommendations,¹⁹ is considered to begin at 3 cd/m². The spatial frequencies used were of 0.5, 1.0, and 2.0 cpd. The frequencies were chosen to ensure the presentation of at least four cycles of the grating (given our field size of 8°), as recommended by Savoy and McCann⁷ and Mullen.^{13,20} These low spatial frequencies also minimize the possibility of any chromatic aberrations (which we have not corrected for) acting as a cue for facilitating chromatic grating detection to the observer.^{21,22}

Apparatus

The stimuli were displayed on a Sony CPD17SF2 color monitor controlled by a VSG2/3 waveform generator (Cam-

bridge Research Systems, Kent, GB) with 14-bit-digital-to-analog converters. The calibration was made with a Topcon SR-1 spectroradiometer under the following assumptions: spatial independence of the phosphors with simple scale factor, temporal stability and phosphor constancy.^{23–25} We repeated the calibration procedure periodically to ensure good color reproduction.

Procedure

Detection thresholds were determined using a two-alternative, forced-choice staircase procedure, in which the test stimulus appeared during one of two intervals of one second's duration; during the other interval a uniform equi-energy stimulus appeared with a luminance equal to the mean luminance of the chromatic grating. The observer indicated the interval within which the test stimulus appeared by saying "one" or "two." The staircase procedure finished after six contrast reversals and the threshold was calculated as the mean of the contrasts of the last four reversals. Each threshold was determined as the mean of at least three measurements, with 1 standard deviation as the error interval. No feedback was given to the observer after an incorrect response, and he/she was not informed about the spatial frequency or the mean luminance of the gratings during the experiment. The viewing distance was 1.68 m (visual field of 8°). A thick black paper with a residual luminance of less than 0.5 cd/m² at the highest mean luminance presented to the observer covered the borders of the viewing field. A chin rest fixed the head position and vision was direct and monocular (left eye for all observers).

Observers

Two males (JH and JL, 28 and 31 years old respectively) and one female (EV, 28 years old) participated in the experiment. All had normal color vision according to standard color-vision tests and were corrected to normal acuity.

RESULTS

Contrast Thresholds for Chromatic and Luminance Gratings

Figure 1a shows the average contrast thresholds found by the three observers for the 2-cpd chromatic gratings. The contrast thresholds diminished with increasing luminance levels, although there were some quantitative differences among the observers. This behavior was similar for all three frequencies, with the lowest contrast thresholds found with the 0.5-cpd chromatic gratings.

Figure 1b shows the average contrast thresholds found by the three observers for the 0.5-cpd luminance gratings. The contrast thresholds diminished with increasing luminance levels at all three frequencies, with the lowest found for the 2.0-cpd gratings. At high luminance levels the contrast threshold entered into a flatter region for both chromatic and luminance gratings, although this region began at lower

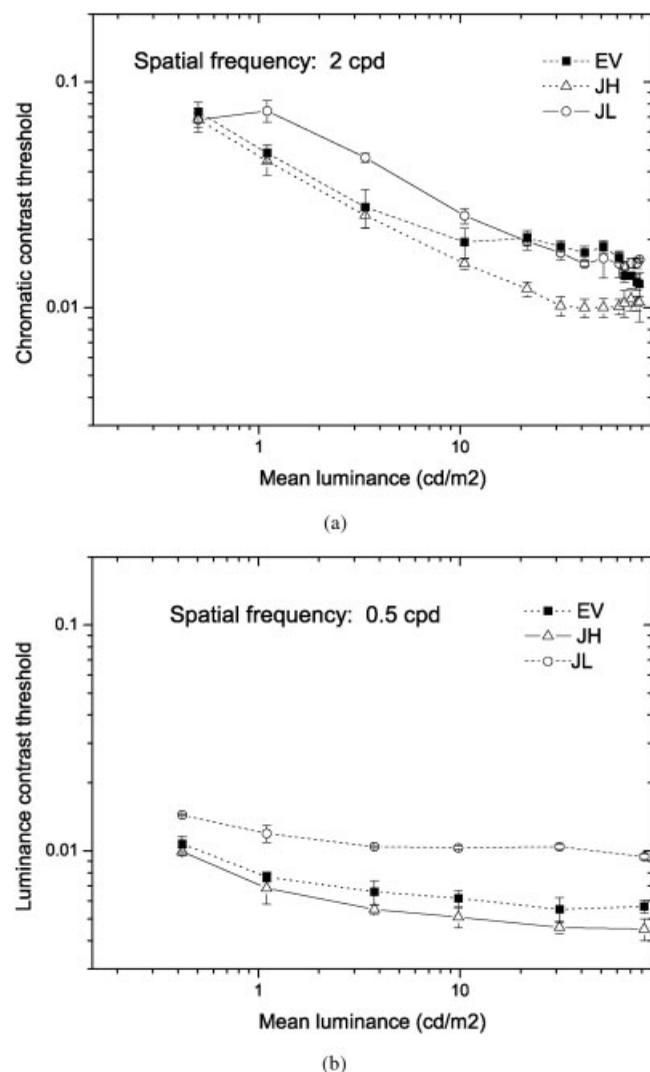


FIG. 1 Average contrast thresholds for each of the three observers as a function of luminance level for (a) chromatic gratings with a spatial frequency of 2.0 cpd and (b) luminance gratings with a spatial frequency of 0.5 cpd.

mean luminance values for luminance gratings. Actually this is consistent with physiological²⁶ and psychophysical²⁷ data.

Determination of the Transition Luminance

The results in Fig. 1 reveal that the changes in contrast threshold with luminance fall into two regions. Determining the transition luminance between either region is far from easy. In earlier studies^{1,2,11,28} two fittings were made for these separate ranges in the experimental data but the identification of the transition luminance between the two fittings is somewhat arbitrary (see Graham,²⁹ pp. 531–532); a decision must be made *a priori* as to which part of the experimental distribution is adjusted to Eq. (1) (DeVries–Rose law) and which part is adjusted using a lower slope than -0.5 in the logarithmic scale. We fitted our data to two-stage distributions with different transition luminances

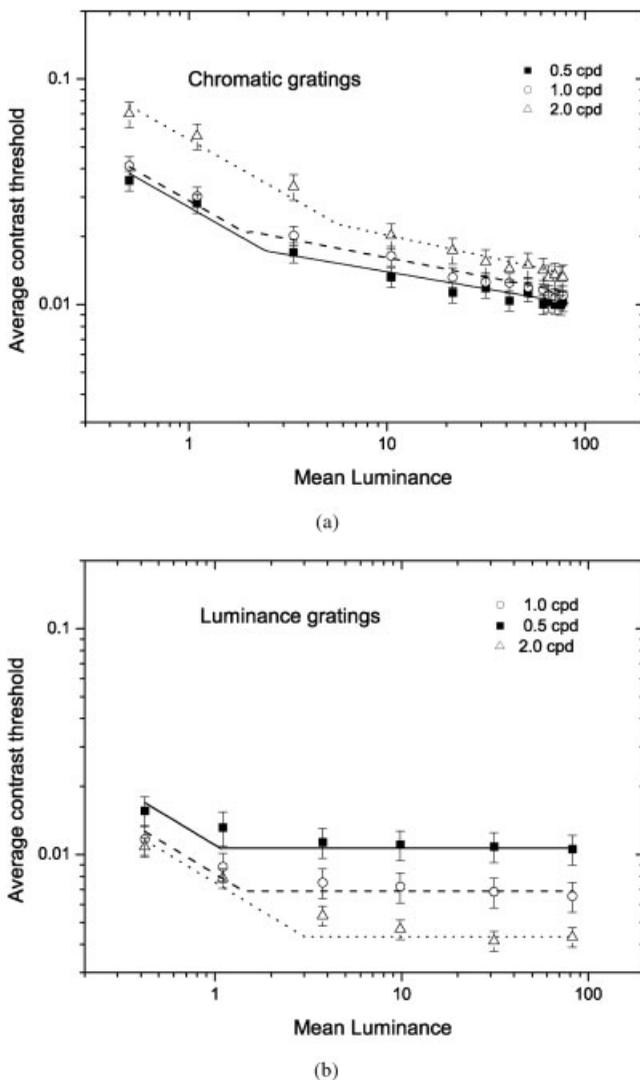


FIG. 2 Average contrast thresholds and theoretical distributions associated to (a) the red–green chromatic gratings and (b) the luminance gratings for the three spatial frequencies used.

until we found the distribution that gave the minimum residual error. Figure 2 shows the data points (average results for all three observers) and the two-stage distributions corresponding to the luminance and the red–green chromatic gratings. The data show vertical shifts along the ordinate axis, the contrast thresholds increasing with the spatial frequency for the chromatic gratings. The two-stage distributions agree reasonably well with our experimental data. The transition luminances determined as the intersection of the two stages are 2.15, 2.01, and 5.75 cd/m^2 for the 0.5-, 1.0-, and 2.0-cpd chromatic gratings respectively and 1.15, 1.79, and 3.09 cd/m^2 for the 0.5-, 1.0-, and 2-cpd luminance gratings respectively. These data were used as qualitative descriptors for the experimental results as we are well aware that the transition luminance values obtained are highly conditioned by the range of mean luminances and the form of the two-stage distribution used. The results suggest that the chromatic and luminance gratings behave differently. With the luminance gratings the transition luminance

increases with spatial frequency, whereas for the red–green chromatic gratings only the highest spatial frequency results in a higher transition luminance value.

DISCUSSION

We have tested the influence of the mean luminance level on detection thresholds for chromatic and luminance gratings. The changes in threshold with the mean luminance level reflect the two different regions reported in earlier studies. Our results with all the spatial frequencies used confirm the validity of the DeVries–Rose law and a flatter region at high luminance values for chromatic gratings, something that had not been tested before. Van der Horst and Bouman¹¹ used luminance levels from 0.024 to 12.75 cd/m^2 , which correspond to retinal illuminances of 0.30 and 160 td when a 2-mm artificial pupil is used (i.e. mesopic and low-photopic levels). Sekiguchi et al.¹⁴ used higher luminance values but studied only one spatial frequency and thus could draw no further conclusions concerning the variation of transition luminance with spatial frequency. We also replicated the experiment with the same spatial frequencies for luminance-varying patterns and again found two different regions in the experimental distributions, in agreement with the DeVries–Rose and Weber laws.^{6,10} Nevertheless, we found no direct proportionality between the transition luminance and the square of the spatial frequency of the grating, as Van Nes and coworkers did.^{3,6} This was also the case for chromatic gratings, given that the transition luminance obtained was not proportional to the square of the spatial frequency. These facts have led us to reconsider whether the constant-flux hypothesis accounts adequately for the dependence of transition luminance on spatial frequency both for chromatic and luminance gratings.

It is well-known that differences exist in the processing of luminance and chromatic gratings by the human visual system.^{11,20} The center and periphery of the cells responding to chromatic gratings receive inputs from different types of cones (i.e., L-cone type to the center and M-cone type to the periphery). Therefore, the center and periphery act synergically for variations in color of the same sign and thus the maximum response of the cell corresponds to a spatial frequency in such a way that one half-cycle covers both the center and the periphery, but the optimum response is also maintained for lower spatial frequencies. This makes the maximum-sensitivity frequency less for chromatic stimuli than for luminance variations and results in no decline in sensitivity for lower frequencies. This low-pass behavior is also supported by physiological evidence at the early visual stages³⁰ and also, somewhat less clearly, at cortical levels.³¹ So we may assume that a low-pass mechanism operates at the retina of the lateral geniculate nucleus in the processing of chromatic gratings.

The bandwidths and peak positions of visual channels that process luminance and red–green gratings have been determined in various different experiments.^{32–36} Although their results are quantitatively different, it can be concluded that the bandwidth for color spatial mechanisms is very

similar to that of luminance spatial mechanisms. Given that the spatial luminance mechanisms cover a wider range of spatial frequencies it is quite obvious that there are more luminance spatial mechanisms than color spatial ones.

The constant-flux hypothesis is usually explained in terms of the width of the center of the receptive field of the cells responding to luminance gratings (Graham,²⁹ p. 532), the area of which is proportional to the inverse square of the maximum-sensitivity spatial frequency for the cell. Because the flux is proportional to this area multiplied by the transition luminance (maximum luminance for which the spatial summation phenomenon holds) the transition luminance must be proportional to the square of the spatial frequency if the flux remains constant for higher luminances than the transition luminance. It might be pointed out that as our chromatic gratings are isoluminant the spatial frequency would not be expected to affect the luminance summation of the cells responding to them. Nevertheless, we must bear in mind that visual mechanisms that respond to isoluminant chromatic gratings may also respond to luminance variations. There is enough electrophysiological evidence to support the idea that the same neurons may respond to both kinds of stimulus (with different receptive-field structures of course). Anyway, the key factor in the constant-flux hypothesis for chromatic gratings is the variation in mean luminance of the gratings rather than an absence of luminance modulation. The signal integration in the receptive field obviously depends on this factor and there is no reason to take into account an integration phenomenon, which only occurs with luminance gratings.

Our data are compatible with the idea that the transition luminance is directly proportional to the spatial frequency of maximum response for the visual channel that processes the grating (either luminance or chromatic), but not to the area of the excitatory center of the receptive field of the cells responding to the grating. Thus for chromatic gratings we have two different channels responding to red-green gratings, one for 0.5 and 1.0 cpd and another for 2.0 cpd. This is in accordance with the peak positions and bandwidths found experimentally for red-green gratings. For luminance gratings, there would be three different channels, responding to gratings of 0.5, 1.0 and 2.0 cpd, and so the transition luminances found are different for the three different spatial frequencies used in our experiment.

We cannot rule out the possibility that our chosen method of determining the transition luminance might affect our results in some way because, as we mentioned earlier, this determination is by no means easy. Nevertheless, we used precisely the same procedure for both the chromatic and luminance gratings and any different method could only have led to quantitative, not qualitative, differences in the transition luminance values obtained.

One additional point to bear in mind is the possible influence of chromatic aberration in our results. We feel, however, that we can justifiably rule out the presence of spurious luminance components due to chromatic aberration. If the threshold established by the observers were determined by luminance changes instead of grating chromaticity, the results would have to be similar to those of the luminance gratings as far as any variation in the threshold with the mean luminance of the stimuli is concerned. The chromatic gratings behave differently, however, making it reasonable to exclude the intrusion of the luminance mechanism into the measurement of the chromatic detection thresholds.

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