Detection of chromoluminance patterns on chromoluminance pedestals I: threshold measurements

Chien-Chung Chen *, John M. Foley, David H. Brainard

Department of Psychology, University of California, Santa Barbara, CA 93106, USA

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Abstract

Measurement of the detection thresholds of patterns on pedestals of various kinds has the potential of providing insight into the mechanisms that mediate pattern vision. This study is concerned with chromoluminance patterns, that is, patterns that vary over space in luminance, chromaticity, or both. Contrast thresholds for 1 c/deg Gabor patterns (targets) were measured as a function of the contrast of Gabor pedestal patterns (TvC functions), where the pedestals paired with each target were modulated in a wide range of directions in color space. For most target-pedestal pairs, the TvC function decreased (facilitation) and then increased as pedestal contrast increased. The increase went above the absolute contrast threshold (masking) for all target-pedestal pairs except in cases where facilitation occurred at the upper end of the pedestal contrast range. The specific form of the TvC function varied greatly with the target and pedestal, consistent with a general model of pedestal effects proposed by Foley [Journal of the Optical Society of America A, 1994, 11(6)]. There were two sets of target-pedestal pairs for which facilitation did not occur, but masking did occur: pairs in which the target was a luminance modulation and the pedestals were individually isoluminant and pairs in which the pedestal was blue/yellow and the target was in any of our directions except blue/yellow. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

In most natural images both the overall intensity and the spectral composition of light vary over space. Such modulation of light across space can be analyzed into the sum of a luminance modulation and a chromatic (isoluminant) modulation. Luminance modulations carry a large amount of information about spatial structure, but the information carried by the chromatic modulation can also be important (e.g. Brill, 1990; De Valois, 1994). Visual processing of luminance patterns has been studied extensively and there is a substantial body of measurements and models relating to it. (For reviews see De Valois & De Valois, 1988; Graham, 1988; Wilson, Levi, Maffei, Rovamo & De Valois, 1990; Regan, 1991.)

In the luminance domain, the experimental paradigm of simultaneous superimposed masking has been used to develop quantitative models of the mechanisms that encode information about spatial patterns (Legge, 1979; Legge & Foley, 1980; Wilson, McFarlane & Philips, 1983; Ross & Speed, 1991; Foley, 1994; Watson & Solomon, 1997). In a simultaneous superimposed masking experiment, the observer's task is to detect a target pattern superimposed on another pattern. The paradigm is sometimes called detection on a pedestal and the second pattern is called the pedestal or masker. An advantage of this paradigm over the absolute threshold paradigm is that it can be used to measure performance over a large range of contrasts.

To date there have been only a few studies that have measured pedestal effects in which target and pedestal are sinewave gratings or Gabor patterns which vary spatially in color. A major purpose of the early studies was to investigate the interaction between luminance and chromatic patterns. Most of these early studies used isoluminant red/green patterns and luminance pat-

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* Corresponding author. Present address: Department of Ophthalmology, University of British Columbia, Room A146, 4480 Oak Street, Vancouver BC, Canada V6H 3V4. Fax: +1-604-8752683.

E-mail address: chen@ski.org (C.-C. Chen).

terns and compared uncrossed pedestal effects (color on color, luminance on luminance) with crossed pedestal effects (color on luminance, luminance on color). These include studies by De Valois and Switkes (1983), Switkes, Bradley and De Valois (1988), Losada and Mullen (1994), Mullen and Losada (1994) and one of the experiments of Gegenfurtner and Kiper (1992). Vimal (1998) has reported similar experiments using a paradigm in which the pedestal is tilted at 14.5° re the target. When target and pedestal had the same color direction, target contrast threshold versus pedestal contrast (TvC) functions were generally 'dipper-shaped' with facilitation at low pedestal contrast and masking at high. The results for the crossed pedestal conditions were more complex. With a luminance target and a red/green isoluminant pedestal, Switkes et al. found masking but not facilitation. With an isoluminant target and a luminance pedestal, they found facilitation over a wide range of pedestal contrast and masking at high pedestal contrast. Gegenfurtner and Kiper (1992) confirmed this result. Mullen and Losada, however, found facilitation and masking in both crossed conditions. Two studies have examined pedestal effects in other color directions (Gegenfurtner & Kiper, 1992; Stromeyer, Thabet, Chaparro & Kronauer, 1999), but they used a single pedestal contrast and did not determine TvC functions.

There are other studies of chromoluminance vision in which the targets and pedestals are spots or blobs and studies in which targets are detected in the presence visual noise. While these studies are related to this one, both their results and the interpretation of them are sufficiently different from it that we consider them in a separate section after we present our results.

The primary goal of this study is to extend our knowledge of chromoluminance pattern vision. We use the term chromoluminance pattern to refer to a spatial modulation in either luminance, chromaticity, or both. Our approach is to exploit the measurement and analytic techniques that have been developed in the study of luminance pattern vision. For a full understanding of the effect of a pedestal on pattern detection, it is essential to measure target detection threshold over a large range of pedestal contrasts (TvC function). A pedestal can have very different effects on target detection as its contrast is varied. At one contrast a pedestal can decrease target threshold while at another contrast it can increase threshold. In general, the shape of TvC functions varies with both the target and the pedestal (Ross & Speed, 1991; Foley, 1994). Analysis of the shapes of TvC functions for different target-pedestal pairs plays a critical role in testing models of pedestal effects and in estimating their parameters (Foley, 1994). Accordingly, we extended previous work by measuring TvC functions for chromoluminance targets in five directions presented on pedestals in many directions.

We selected five target modulations along different lines in color space, one luminance and four isoluminant (varying in chromaticity only). Two of the isoluminant targets were modulated in the cardinal directions: one cardinal direction produces modulation in S-cones only while the other produces opposite-sign modulations in the L- and M-cones and does not affect the S-cones (MacLeod & Boynton, 1979; Krauskopf, Williams & Heeley, 1982; Derrington, Krauskopf & Lennie, 1984). The other two targets were in intermediate directions. The pedestal modulations were along the five directions of our targets plus eight other directions that combined luminance and chromatic modulations. All patterns had the same Gaussian enveloped sinewave (Gabor) spatial profile.

This paper describes our experiment and data, while the companion paper (Chen, Foley & Brainard, 2000) provides a quantitative model and interprets our results in terms of mechanism properties.

2. Methods

2.1. Stimuli

Patterns were presented in a rectangular field (5°V × 7°H) and viewed from a distance of 162 cm. There was a small dark fixation point in the center of the field. Both targets and pedestals were horizontal Gabor patterns with a center spatial frequency 1 c/deg. The scale parameter (standard deviation) of the Gaussian spatial envelope was 1° in both horizontal and vertical directions. The patterns were modulated in cosine phase relative to the fixation point and to the peak of the envelope. All modulations were around a single white point with CIE xy chromaticity (0.28, 0.31) and luminance 29.6 cd/m². The background was this same white and was on continuously. All stimuli were presented using a truncated Gaussian temporal waveform with a scale parameter of 40 ms and a total duration of 160 ms. Target and pedestal were always coincident in time and superimposed in space.

The chromatic modulation of the targets and pedestals was always along a straight line in cone excitation space. Such a modulation can be represented by a cone contrast vector (Brainard, 1996) at each point in space. In our experiments, however, since our spatial modulations always have the same Gabor form, differing only in that some of them are of opposite sign, we can describe the contrast by giving the three cone contrasts at the center of the pattern. We will refer to these as the cone contrasts of the pattern. The L-cone contrast of the pattern, C_L, is defined as $\Delta L/L_0$ where L_0 is the L-cone excitation produced by the background and $\Delta L = L - L_0$ is the L-cone excitation deviation at the central point of the pattern. If there is a decrement

in cone excitation at the central point, then the cone contrast is negative. The M-cone and S-cone contrasts, C_M and C_S, are defined similarly and the chromoluminance modulation is given by the column vector $C = [C_L, C_M, C_S]^T$. Note that, if the phase of the underlying co-sinusoidal grating is shifted by 180°, the direction of the vector reverses. Cone excitations and contrasts were calculated using the Smith–Pokorny estimates of the cone spectral sensitivities (Smith & Pokorny, 1975; DeMarco, Pokorny & Smith, 1992). For calculations, each sensitivity was normalized to a maximum of one and spectra were expressed in units of watts/($sr - m^2 - nm$). Notice that all our patterns contain chromoluminance modulation about a single background. Therefore, defining the stimuli in cone contrast is more intuitive than in cone excitation. The specification of the stimuli in terms of contrast rather than cone excitation is based on the hypothesis that the visual system response is more closely related to contrast than to excitation (Walraven, Enroth-Cugell, Hood, MacLeod & Schnapf, 1990; Brainard, 1996). If the cone excitation vector of the background is known, one can transform from contrast to excitation. The LMS cone excitation vector of the background was $[0.044, 0.040, 0.033]^T$.

Table 1
Experimental stimuli[a]

Name	Chromoluminance direction (C_L, C_M, C_S)
Luminance	[0.577, 0.577, 0.577]
Green/red	[−0.486, 0.874, 0.000]
Blue/yellow	[0.000, 0.000, 1.000]
Blue-green/orange	[−0.343, 0.618, 0.707]
Yellow-green/purple	[−0.344, 0.618, −0.707]
Green-red + luminance	[0.059, 0.928, 0.369]
Blue-yellow + luminance	[0.325, 0.325, 0.888]
Blue-green/orange + luminance	[0.132, 0.675, 0.726]
Yellow-green/purple + luminance	[0.191, 0.976, −0.106]
3 × Green/red + luminance	[−0.212, 0.956, 0.205]
Green/red + 3 × luminance	[0.323, 0.806, 0.496]
3 × Blue/yellow + luminance	[0.186, 0.186, 0.965]
Blue/yellow + 3 × luminance	[0.449, 0.449, 0.772]
Green-red (ii for CCC)[b]	[−0.752, 0.655, 0.076]
Yellow-blue (ii for CCC)[b]	[0.0006, −0.054, −0.999]

[a] Each chromoluminance direction is specified by name and by direction. The names are for identification purposes only and may not describe color appearance. In naming the stimuli we give the color of the stripe through the fixation point first then a slash (/) followed by the flanking color. The color chromoluminance directions are normalized to have a vector length of 1.

[b] These pedestal directions were approximately individually isoluminant for CCC. They were used in a supplementary experiment to test the hypothesis that these pedestals will mask, but not facilitate, the detection of a luminance target.

We specify modulations in terms of their contrast and chromoluminance direction. Chromoluminace direction is given by the normalized vector, $C/\|C\|$, where the notation $\|C\|$ denotes the length of the vector C. There are a number of different measures that have been used to specify contrast across different chromoluminance directions. Here we define the contrast of a modulation as:

$$c = (C_L^2 + C_M^2 + C_S^2)^{0.5}/(3)^{0.5}. \qquad (1)$$

This measure is proportional to the square-root of cone contrast energy and varies between 0 and 1, the same range as Michelson contrast. Although we use this definition to describe our stimuli and results, we do not draw conclusions that depend on the comparison of contrast across modulation chromoluminance directions. Contrast is often expressed in dB re 1 which equals $20 \log_{10} c$.

The description of modulation direction can be combined with a description of the spatial waveform to specify the cone excitation $K(x, y)$ at each point in the stimulus. This is the vector valued function given by:

$$K(x, y)$$
$$= BG + BG.* C \cos(2\pi y) \exp(-x^2/2\sigma^2 - y^2/2\sigma^2) \qquad (2)$$

where x and y are the distances in degrees from the fixation point, σ is the standard deviation of the Gaussian in degrees, BG is a three by one vector that specifies the cone excitation coordinates of the background, and the symbol .* denotes element by element multiplication of two vectors.

Table 1 provides a name and the L, M, and S cone contrasts for each of the modulation directions used. For some of the directions, we found it helpful to use descriptive color names. In these cases, a name describing the color appearance of the stripe through the fixation point is given first, followed by a slash (/), followed by a name for the flanking stripe. The names are those used most frequently by our observers when they were asked to describe the stimuli. They are not complete descriptions of the hues seen. This means that, for example, the colors of the stripes in the blue/yellow direction were not necessarily unique blue and unique yellow. The specified cone contrasts in the table correspond to the normalized vector $C/\|C\|$.

The first three directions in Table 1 are modulations in cardinal directions (MacLeod & Boynton, 1979; Krauskopf et al., 1982; Derrington et al., 1984). The first direction is a luminance modulation. The next four directions are nominally isoluminant because they are orthogonal to the Judd–Vos photopic luminosity function V_λ (Vos, 1978), which corresponds to the normalized column vector $[0.826, 0.564, 0]^T$ in the cone contrast space. The next eight directions may be thought of as mixtures of a nominally isoluminant

modulation and the luminance modulation. The final two directions were used in supplementary conditions for observer CCC.

2.2. Isoluminance

In contrast with other studies of pedestal effects with chromoluminance patterns, in our main experiment we did not tailor our stimuli to the individually isoluminant planes of the observers. The term individually isoluminant plane refers to the isoluminant plane defined for an individual observer by flicker photometry or a related technique. Flicker photometric measurements of the isoluminant plane show considerable inter-observer variability (Wyszecki & Stiles, 1982). For this reason, many investigators choose to measure each observer's individually isoluminant plane and select stimuli in this plane (Switkes et al., 1988; Sekiguichi, Williams & Brainard, 1993; Losada & Mullen, 1994). A consequence of this procedure is that each observer is presented with different stimuli.

This use of individually isoluminant stimuli is justified by the hypothesis that flicker photometry is mediated by the same mechanisms as those that mediate luminance pattern vision, so that flicker photometry can be used to identify stimuli that do not excite luminance pattern vision mechanisms. Although there is evidence that supports this hypothesis, it has not been directly established. We have chosen instead to define isoluminance by the Judd–Vos photopic luminosity function V_λ (Vos, 1978) and to use the same set of nominally isoluminant stimuli for all our observers in our main experiment. For our purpose the directions of the stimuli used are not critical. We simply wanted to examine a large range of directions. Our nominally isoluminant stimuli lie on a plane in the color space that is orthogonal to the direction defined by the V_λ function. Except where stated otherwise, the term isoluminance in this paper refers to nominal isoluminance rather than individual isoluminance determined psychophysically. We did, however, determine the individually isoluminant planes for our observers and performed a supplementary experiment using an individually isoluminant pedestal.

2.3. Isochrominance

Our luminance modulation has the property that the relative excitations of the L, M, and S cones remain constant, as does the CIE chromaticity. In this sense, the luminance modulation is physically isochromatic. On the other hand, there is no accepted method for determining what modulation silences the chromatic mechanisms. It is, therefore, not certain that the luminance modulation is perceptually isochromatic, either on average or for individual observers.

2.4. Equipment

Target and pedestal patterns were presented on separate color monitors (Sony CPD-1730) each driven by its own graphics board (RasterOps Turbo XL). Each graphics board provided 9 bits of intensity resolution in each color channel. The two graphics boards were controlled by a single host computer (Macintosh IIfx). The output of the two monitors was optically combined by a beam-splitter. We used two beam splitters with different transmission ratios in different conditions as a means of adjusting the contrast range of our stimuli. Refresh timing of the two monitors was synchronized with custom software, and target and pedestal contrasts could be varied simultaneously during a single vertical blanking period. The frame rate of the monitors was 75 Hz. The monitors had a spatial resolution of 832 horizontal by 624 vertical pixels. At the distance we used (162 cm), there were 76 pixels per grating cycle.

We measured our monitors' red, green, and blue phosphor spectral power distributions and overall input–output intensity functions using a PhotoResearch PR-650 spectraradiometer. This information allowed us to compute the appropriate frame buffer and lookup table settings to produce any desired cone excitation coordinates at each location on the screen (Brainard, 1989). We verified by direct measurement of square wave gratings that the actual cone contrasts produced by our monitor control procedure were close to their nominal values. With a few exceptions, the differences between the nominal and measured values were below the detection thresholds of all our observers. The lookup table settings for each beam-splitter were based on the phosphor spectral power distributions and overall input–output intensity functions measured through that beam-splitter. We used a theoretical model (Marimont & Wandell, 1993) to verify that axial chromatic aberration did not significantly distort the separate L, M, and S cone contrasts of our 1 c/deg stimulus. The experimental control software was written in MATLAB (The MathWorks Inc., 1993) using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

2.5. Procedure

To measure contrast threshold, we used a temporal two-alternative forced choice procedure in which the pedestal alone was presented in one interval and the target and pedestal superimposed were presented in the other interval. The observers were specifically instructed to make decisions based on the overall contrast difference between two intervals and not on local chromoluminance differences. Two observers, in a pilot experiment, tried to make decisions based on the chromoluminance difference of the central stripes of the pedestal-alone and the target-plus-pedestal and did not

Table 2
Experimental design[a]

Target	Luminance	Green/red	Blue/yellow	Blue-green/orange	Yellow-green/purple
Pedestal					
Luminance	X	X	X	X	X
Green/red	X	X	X	X	X
Blue/yellow	X	X	X	X	X
Blue-green/orange	X	X	X	X	X
Yellow-green/purple	X	X	X	X	X
Green/red + luminance	X	X			
Blue/yellow + luminance	X		X		
Blue-green/orange + luminance	X			X	
Yellow-green/purple + luminance	X				X
$3 \times$ Green/red + luminance	X				
Green/red + $3 \times$ luminance	X				
$3 \times$ Blue/yellow + luminance	X				
Blue/yellow + $3 \times$ luminance	X				

[a] An X in a cell indicates that the corresponding target-pedestal pair was used in the main experiment

perform better than when making decisions based on the overall contrast. Therefore, the effects we found in this study are unlikely to be due to the use of local cues (Mullen & Losada, 1994). The interstimulus interval was 480 ms. Target contrast for each trial was chosen using the Quest adaptive procedure (Watson & Pelli, 1983; Pelli & Farrell, 1995).

2.6. Experimental design

Table 2 shows the target-pedestal pairs that were used in the main experiment. There were five target patterns, one luminance and four nominally isoluminant. The pedestals were these same five patterns (principal pedestals) plus eight other patterns that combined luminance and chromatic modulations. Each target was paired with the five principal pedestals and one or more of the other pedestals. There were 39 target-pedestal pairs used. All the observers had at least several hours of practice before the experiment began. For each target-pedestal pair, target thresholds were measured for 9–11 pedestal contrasts. The pedestal contrasts ranged from about 12 dB (0.6 log units) below the detection threshold of the pedestal to the highest contrast our equipment could produce in that chromoluminance direction. We also measured the absolute contrast threshold for each target (the threshold at 0 pedestal contrast). Reported thresholds are the mean of four or six individual measurements made in separate sessions. The experimental conditions were blocked by the targets. The order of pedestals was randomized for each target.

There were two principal observers, one of the authors (CCC, male in his late twenties) and one naive observer (JKL, female in her early twenties). Since JKL had a very high threshold for the blue/yellow target, another author, JMF (male, in his late fifties) substi-

tuted for her in conditions using this target, as well as observing in some of the other conditions. All observers had normal (20/20) or corrected to normal visual acuity and normal color vision as tested with the Ishihara plates (Ishihara, 1977).

3. Results

There were 39 target-pedestal pairs and at least two observers for all but three. In this paper, we plot a subset of the TvC functions, those that illustrate the main empirical findings. The entire data set is available in numerical form on the world wide web at URL http://color.psych.ucsb.edu/chromolum/.

We divide the description of the results into five sections based on the chromoluminance directions of the target and pedestal: (1) target and pedestal in the same color direction; (2) isoluminant target on isoluminant pedestal; (3) isoluminant target on luminance and mixed pedestals; (4) luminance target on isoluminant pedestal, and (5) luminance target on mixed pedestal.

In the graphs there are axes for percent contrast on a log scale and for contrast in dB re 1. All of the smooth curves shown in the graphs correspond to the best fit of a model to the entire data set of the observer. The model is described in the companion paper.

3.1. Target and pedestal in same chromoluminance direction (contrast discrimination)

Figs. 1 and 2 show TvC functions for conditions in which the target and the pedestal were modulated along the same direction in color space. Fig. 1 shows TvC functions for cardinal directions and Fig. 2 for intermediate isoluminant color directions. All TvC functions have a dipper shape, typical of that reported in the
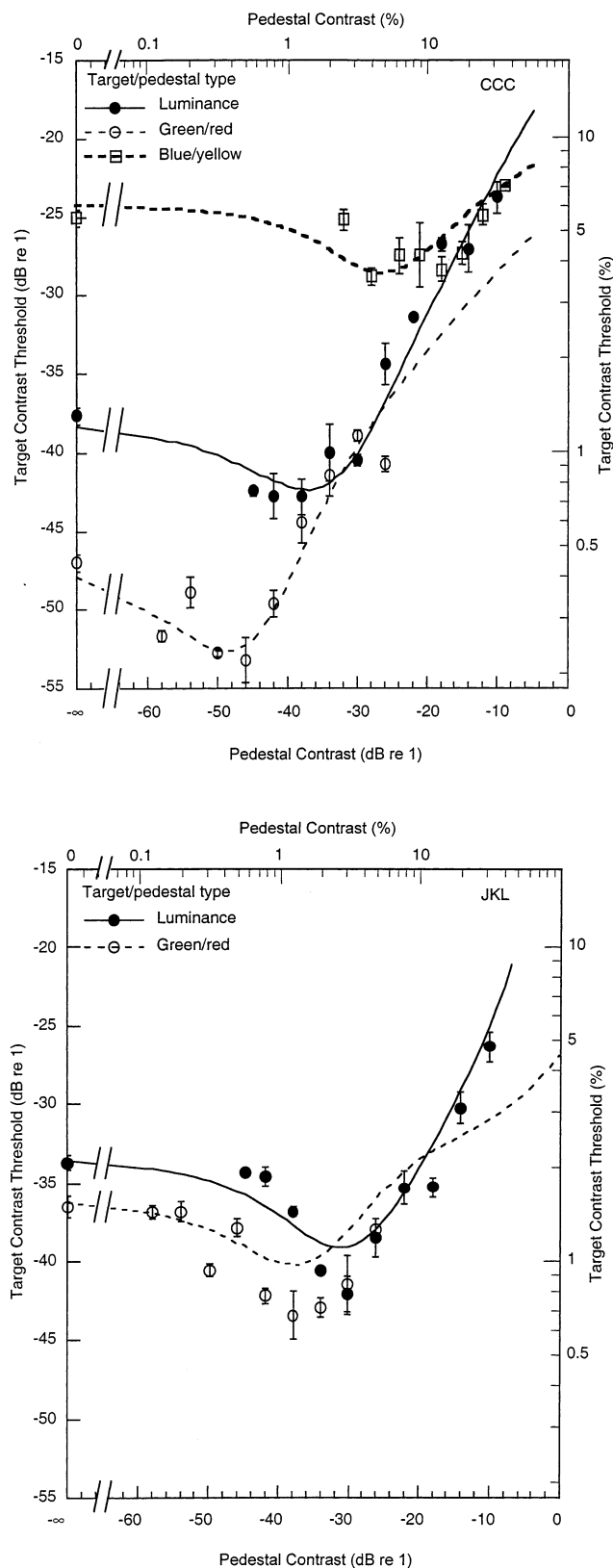
Fig. 1. TvC functions for the conditions in which the target and the pedestal are modulated along the same direction in color space: cardinal directions. Each panel shows data for one observer. The smooth curves show the model fit.
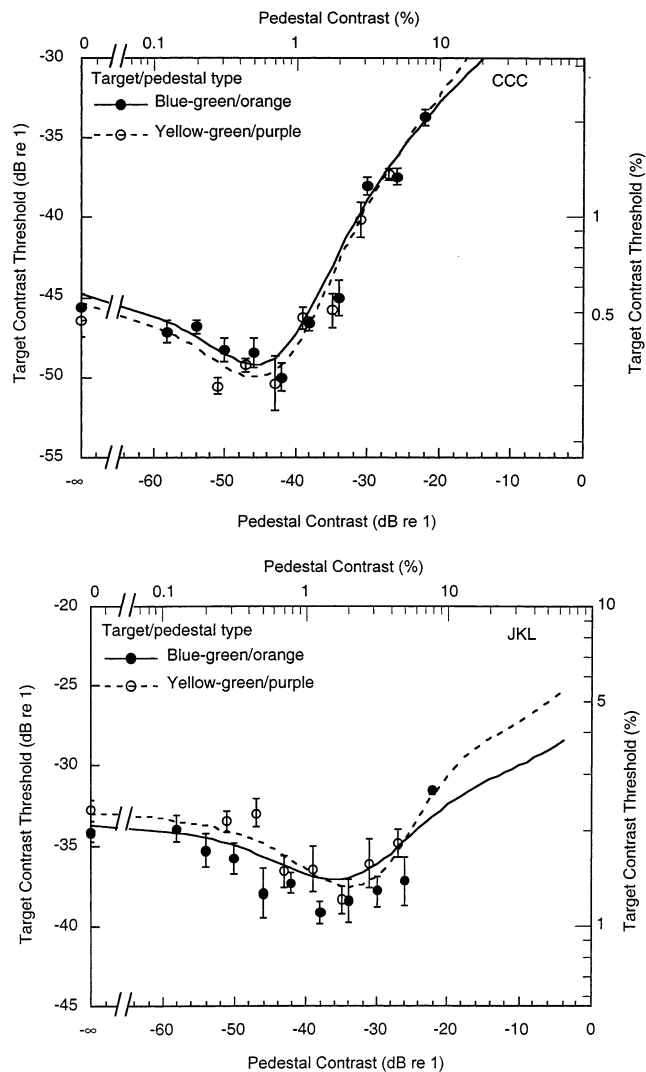
Fig. 2. TvC functions for the conditions in which the target and the pedestal are modulated along the same direction in color space: intermediate directions. Same format as Fig. 1.

luminance pattern detection literature. That is, the target threshold first decreases (facilitation) and then increases (masking) with pedestal contrast. The greatest facilitation occurs when the pedestals are near their own absolute thresholds. JKL is less sensitive to all four isoluminant targets than our other observers. As a result, we were not able to test her with the blue/yellow target and her absolute thresholds for the other isoluminant targets are near the end of our pedestal contrast range and we were not able to test in the range where masking would be expected.

The TvC functions for the luminance and green/red isoluminant patterns have almost the same 'dipper-shaped' form as was reported by Switkes et al. (1988). The TvC functions for the two intermediate isoluminant stimuli (Fig. 2) are similar.

3.2. Isoluminant targets on isoluminant pedestals

Fig. 3 shows TvC functions for a green/red isoluminant target on other isoluminant pedestals. The blue/yellow pedestal has little, if any, facilitation effect on green/red target detection, but for CCC it does substantially mask the green/red target. The small facilitation from blue/yellow pedestal to green/red target for JKL suggests that her green/red detection mechanism may receive some positive S-cone input as well. It is unlikely that facilitation would occur at pedestal contrasts below the measured range, because these contrasts are well below the absolute threshold for the blue/yellow direction. The TvC functions for pedestals in intermediate directions all have a dipper shape, similar to that for the green/red pedestal (see Fig. 1a, b).

Fig. 4 shows TvC functions for the blue/yellow target for CCC and JMF on the other three isoluminant pedestals. All TvC functions show facilitation, and all
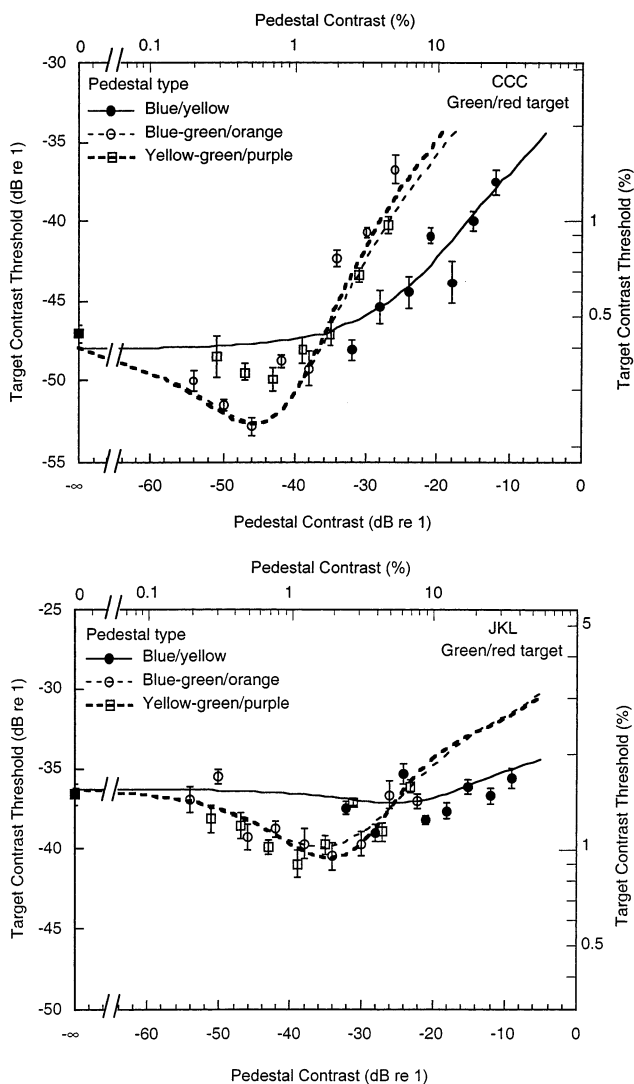

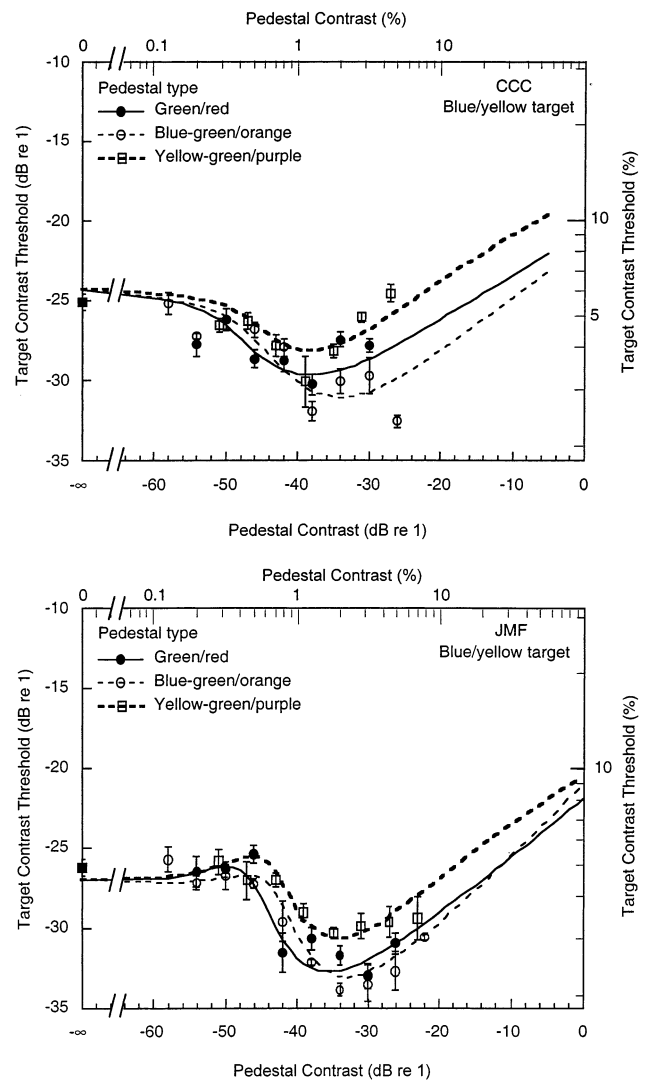Fig. 3. TvC function for a green/red isoluminant target on various isoluminant pedestals.

Fig. 4. TvC function for a blue/yellow isoluminant target on various isoluminant pedestals.

thresholds increase at high pedestal contrasts. The highest pedestal contrasts used were at the upper limit of our apparatus and in most cases the contrast thresholds at the upper limit are still below the absolute threshold.

The TvC functions for the two intermediate isoluminant targets on isoluminant pedestals (not shown) are very similar to those for the green/red target. Thus, three of our four isoluminant patterns, green/red, blue-green/orange, and yellow-green/purple, all facilitate and mask detection of the others and produce similar TvC functions. The blue/yellow pattern does not facilitate the detection of the others (Fig. 3). TvC functions for the detection of the blue/yellow pattern are not as well determined as the others because the pedestal effects occur near the upper limit of the pedestal range, but it is clear that detection of the blue/yellow pattern is facilitated by all four isoluminant patterns and that thresholds are increasing at the upper limit of the pedestal contrast range (Fig. 4).

3.3. Isoluminant targets on luminance and mixed pedestals

Fig. 5 shows TvC functions for a green/red target on a luminance pedestal and a mixed pedestal with equal green/red chromatic and luminance contrast components. The luminance pedestal facilitates green/red target detection. Unlike the TvC curves shown above, however, the region of facilitation extends over a wide range from near-threshold to well-above the pedestal's contrast threshold. Switkes et al. (1988) and Mullen and Losada (1994) have reported a similar effect. The mixed pedestal produces a dipper-shaped TvC function much like that produced by the green/red pedestal. The data for the intermediate isoluminant targets are very similar to those for the green/red target and are not shown.

Fig. 6 shows TvC functions for a blue/yellow target on a luminance (CCC and JMF) and a mixed pedestal
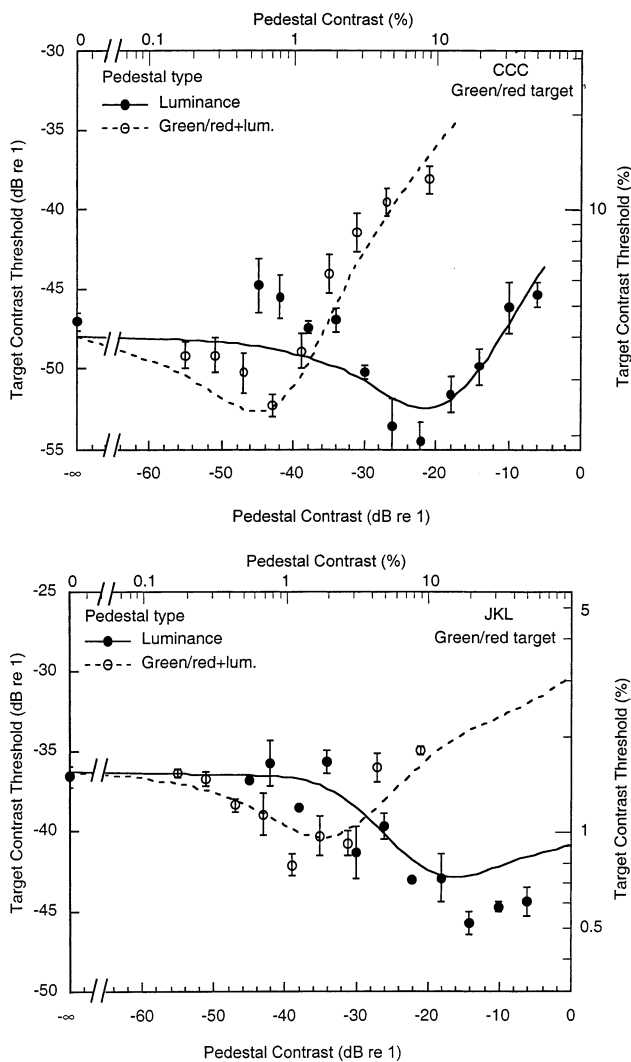

Fig. 5. TvC function for green/red isoluminant target on pedestals containing luminance contrast.
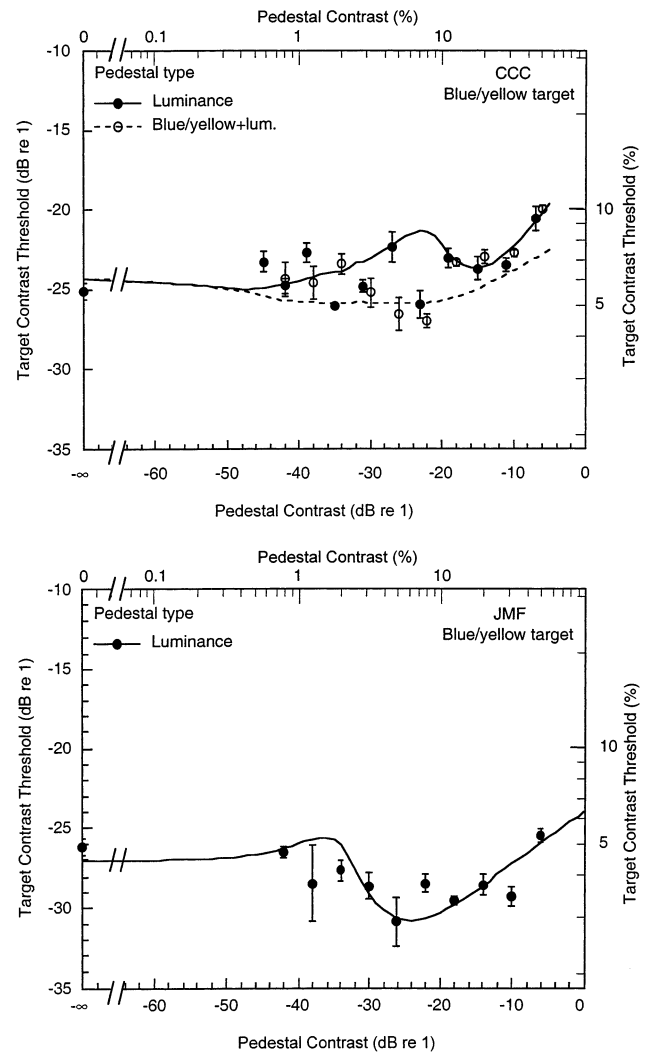

Fig. 6. TvC function for blue/yellow isoluminant target on pedestals containing luminance contrast.

with equal blue/yellow chromatic contrast and luminance contrast components (CCC). For JMF, the effect of the luminance pedestal on the blue/yellow target is similar to its effect on the other isoluminant targets; it produces facilitation and masking at high pedestal contrasts. For CCC, the function is irregular, although there is a local minimum at about −15 dB. The mixed pedestal produces a dipper-shaped TvC function much like that produced by the blue/yellow pedestal.

3.4. Luminance targets on isoluminant pedestals

The effect of chromatic contrast on luminance target detection is quite different from that of luminance contrast on isoluminant target detection. Fig. 7 shows the TvC functions for a luminance target on isoluminant pedestals. For JKL, the isoluminant pedestals cause little, if any, facilitation but do cause masking. Switkes et al. (1988) and Mullen and Losada (1994) reported this for a green/red pedestal. For CCC, the

isoluminant pedestals do produce some facilitation, although it is somewhat weaker than that for other target-pedestal pairs.

Recall that we used nominally isoluminant stimuli. To determine whether the facilitation that occurred for CCC, but not JKL, was due to a difference between nominal and individual isoluminance for CCC, but not
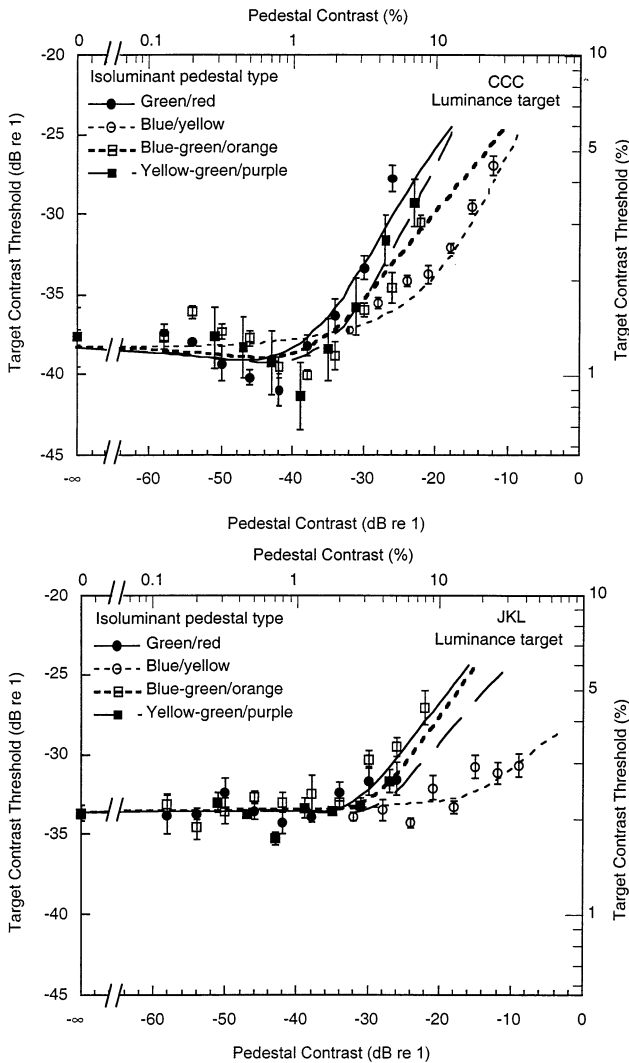

Fig. 7. TvC functions for a luminance target on isoluminant pedestals.

Table 3
The sensitivity of the nominal luminance mechanism (V_λ) and the individual luminance mechanisms as measured by flicker photometry[a]

Observer	Sensitivity [L, M, S]
V_λ	[0.828, 0.561, 0.000]
CCC	[0.620, 0.777, -0.108]
JKL	[0.803, 0.591, -0.076]
JMF	[0.698, 0.713, -0.064]

[a] Sensitivities are expressed as vectors in cone contrast space and each vector is normalized to have a vector length of one.
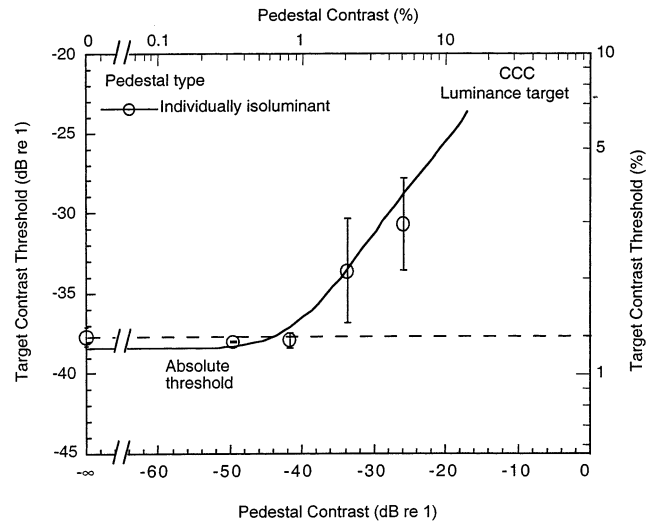

Fig. 8. TvC for a luminance target on a pedestal that was individually isoluminant for observer CCC.

JKL, we used flicker photometry to measure their individually isoluminant planes (see Appendix). The individually isoluminant plane for CCC differs from the nominal isoluminant plane, while that for JKL is in reasonable agreement with the nominal plane. In Table 3 we give the direction of the individual luminance mechanism for each observer. This mechanism is orthogonal to the individually isoluminant plane. For comparison we give the direction of V_λ, the nominal luminance mechanism. The individual difference in isoluminance does suggest that the facilitation shown in Fig. 7 for observer CCC could be due to the deviation of our isoluminant pedestal from his individually isoluminant plane. To test this, two pedestals approximately in CCC's individually isoluminant plane were used in a supplementary experiment. One was green/red and the other, yellow/blue. Their directions are given in Table 1. Fig. 8 shows the TvC function for the green/red individually isoluminant pedestal. The individually isoluminant pedestal produces masking but essentially no facilitation of luminance target detection. The same result was found for the yellow/blue pedestal. Thus, we conclude that individually isoluminant pedestals do not facilitate luminance target detection, and the facilitation effect in CCC's TvC functions shown in Fig. 7 is a consequence of the fact that the nominally isoluminant stimuli are not individually isoluminant for this observer.

3.5. Luminance targets on mixed pedestals

Fig. 9 shows the TvC functions for luminance target on three mixed pedestals with the ratio of luminance contrast to green–red contrast varying from 1/3 to 3. As the ratio increases the masking range shifts to higher pedestal contrasts and the magnitude of facilitation

increases. So the form of the TvC function changes in a regular way as the difference between pedestal and target changes.

For pedestals that are mixtures of luminance contrast and blue/yellow contrast (not shown), the picture is less clear. The magnitude of facilitation remains approximately constant as the ratio changes and the TvC function seems to be largely determined by the luminance contrast.

Table 4 shows in which conditions facilitation occurred for each observer and Table 5 shows in which conditions masking occurred. Note that masking always occurred except when the pedestal contrast range in which masking would be expected was above the range of our apparatus.
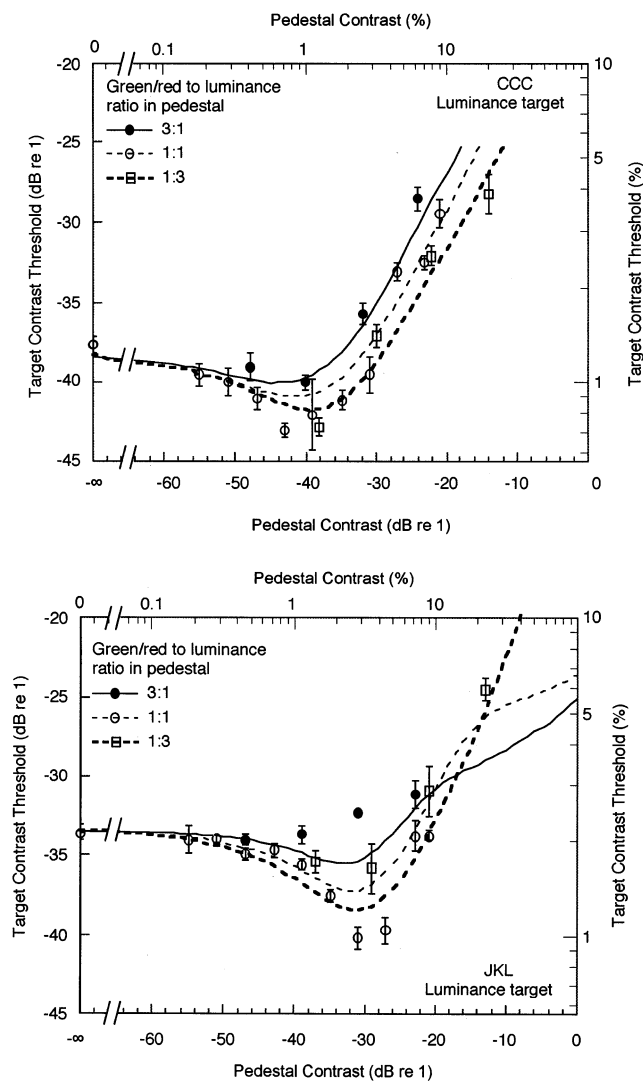

Fig. 9. TvC functions for luminance target on pedestals with various green/red to luminance contrast ratio.

4. Discussion

4.1. Comparison with results in the literature

4.1.1. Sinewave and Gabor patterns

In our conditions in which target and pedestal had the same chromoluminance direction, we found facilitation at low pedestal contrasts and masking at high (a dipper shape, Figs. 1 and 2). This confirms the result of Switkes et al. (1988) and Mullen and Losada (1994) for luminance and red/green stimuli and extends it to three other directions. When our target was a luminance pattern and the pedestal was individually isoluminant we found masking but no facilitation (Fig. 8). This agrees with the result of Switkes et al. (1988) and Gegenfurtner and Kiper (1992), but not with the result of Mullen and Losada (1994), who found facilitation at mid-range mask contrasts (well above mask threshold) and masking at high contrasts in this condition. This facilitation could occur if their isoluminant pedestals excited the luminance mechanism. However, that is unlikely because Mullen and Losada determined isoluminance for their individual observers. Their different result seems likely to be due to a difference in method. Unlike in the other experiments, the phase of their patterns varied randomly from interval to interval in a two-alternative forced-choice procedure. This introduced phase uncertainty. A visible mask would indicate the phase of the target thus reducing phase uncertainty and thereby reducing the threshold.

When our target was an isoluminant pattern on a luminance pedestal we found facilitation at mid-range pedestal contrasts and masking at high, provided that there was a sufficient contrast range (Figs. 5 and 6). This agrees with the results of Switkes et al. (1988); Gegenfurtner and Kiper (1992), Mullen and Losada (1994). The facilitation effect in this condition could occur if the luminance pedestal excites one or more chromatic mechanisms. It has not been definitely established that a physically isochromatic stimulus such as we used is sufficient to isolate the luminance mechanism, although there is evidence that under some conditions such a chromoluminance direction is approximately orthogonal to the red/green mechanism (Eskew, McLellan & Giulianini, in press). Stromeyer et al. (1999) measured thresholds at a single mask contrast. They found neither cross facilitation nor cross masking in either direction. The absence of cross facilitation in the isoluminant target, luminance pedestal condition and the absence of cross masking in either condition is inconsistent with most of the results in the literature and our own. There are two possible reasons for the inconsistency. First, their lack of pedestal effects may be a consequence of the specific, single, pedestal contrast that they used. Second, they used dynamic patterns as masks. These may act more like noise

Table 4
Facilitation. The two entries in a cell correspond to the two observers, JKL (or JMF) and CCC[a]

Target	Luminance	Green/red	Blue/yellow	Blue-green/orange	Yellow-green/purple
Pedestal					
Luminance	1, 1	1, 1	1, 1	1, 1	1, 1
Green/red	0, 1[b]	1, 1	1, 1	1, 1	1, 1
Blue/yellow	0, 0	0, 0	1, 1	0, 0	0, 0
Blue-green/orange	0, 1	1, 1	1, 1	1, 1	1, 1
Yellow-green/purple	0, 1	1, 1	1, 1	1, 1	1, 1
Green-red+luminance	1, 1	1, 1			
Blue-yellow+luminance	1, 1		N, 1		
Blue-green/orange+luminance	1, 1			1, 1	
Yellow-green/purple+luminance	1, 1				1, 1
3xGreen/red+luminance	0, 1				
Green/red+3xluminance	1, 1				
3xBlue/yellow+luminance	1, 1				
Blue/yellow+3xluminance	1, 1				

[a] N indicates no measurement
[b] When an individually isoluminant g-r pedestal was substituted for this nominally isoluminant one, there was no facilitation.

Table 5
Masking[a]

Target	Luminance	Green/red	Blue/yellow	Blue-green/ orange	Yellow-green/ purple
Pedestal					
Luminance	1, 1	X, 1	1, 1	X, 1	X, 1
Green/red	1, 1	X, 1	X, X	1, 1	X, 1
Blue/yellow	1, 1	1, 1	1, 1	1, 1	1, 1
Blue-green/orange	1, 1	X, 1	X, X	1, 1	X, 1
Yellow-green/purple	1, 1	X, 1	X, X	X, 1	X, 1
Green/red+luminance	X, 1	1, 1			
Blue/yellow+luminance	1, 1		N, 1		
Blue-green/orange+luminance	1, 1			1, 1	
Yellow-green/purple+luminance	1, 1				1, 1
3xGreen/red+luminance	1, 1				
Green/red+3xluminance	1, 1				
3xBlue/yellow+luminance	1, 1				
Blue/yellow+3xluminance	1, 1				

[a] X indicates that the contrast range in which masking would be expected is higher than the range of our apparatus

masks, which do not generally produce either facilitation or cross-masking. (See section on research with other kinds of patterns below.)

In addition to examining crossed and uncrossed pedestal effects we have measured TvC functions for targets and pedestals that are in different directions within the isoluminant plane. Here we again found dipper-shaped TvC functions except when the pedestal was blue/yellow and the target was in any of the other three isoluminant directions. Finally, we have studied the effects of pedestals that are mixtures of luminance contrast and chromatic contrast and shown that TvC functions change form systematically with the ratio of the two contrasts. Across our conditions, TvC functions for green/red, blue-green/orange, and yellow-green/purple targets were similar.

As Table 4 shows, we found facilitation to be very common: all targets were facilitated by pedestals having many directions in color space. Exceptions occurred for the blue/yellow pedestal for all targets except blue/yellow and for the luminance target on individually isoluminant pedestals. Masking (Table 5) is even more pervasive. Every target is masked by every pedestal, except in cases where facilitation occurs at the end of the pedestal contrast range. In these cases there is no reason to doubt that masking would occur if the range could be increased.

In summary, our results show that for most target-pedestal pairs both facilitation and masking occur. The specific form of the TvC functions varies greatly. Masking always occurs if the pedestal contrast range is long enough. Facilitation does not always occur. One of the

cases where facilitation does not occur is the case in which a luminance target is detected on a individually isoluminant pedestal.

4.1.2. Spot and blob targets

There is research on chromoluminance masking in which the target and the pedestal are spots or blobs (regions in which chromoluminance is modulated in one direction relative to the background). It would not be surprising if different results were obtained with such stimuli. Since the spatial configuration of these patterns is different then ours, they will excite mechanisms with different spatial sensitivities, and there is evidence that mechanisms with different spatial sensitivities differ in other properties, including their chromoluminance sensitivities. For example, Switkes et al. (1988, Fig. 9b) found that the cross masking of a red–green target by a luminance pedestal becomes very weak at spatial frequencies below 0.5 c/deg.

Studies on contrast discrimination with spots show that facilitation occurs at low pedestal contrast and masking at high (Legge & Kersten, 1983; Whittle, 1986; Cole, Stromeyer & Kronauer, 1990), although Wandell (1985) found that when the stimuli have a Gaussian temporal waveform neither effect occurred. Cole et al. also studied cross pedestal effects with luminance and chromatic spots. In the chromatic target on luminance pedestal case they found facilitation when the pedestal was above threshold. This facilitation remains approximately constant when pedestal contrast is increased. Further, the facilitation is the same whether the pedestal is an increment or a decrement and it is not tuned to the relative chromoluminance directions of target and mask. A similar TvC function was found in the luminance target on chromatic pedestal case. The form of these TvC functions suggests that there is no cross masking for these stimuli and there is a different facilitatory process operating. Several experiments have been done to examine the cross facilitation effect that occurs with spot stimuli (Cole et al., 1990; Eskew, Stromeyer, Picotte & Kronauer, 1991; Chaparro, Stromeyer, Kronauer, & Eskew, 1994). The results of all of these are consistent with the hypothesis that the cross-facilitation that occurs with spot stimuli has a different basis than the facilitation that is frequently observed with sinewave or Gabor patterns.

Krauskopf and Gegenfurtner (1992) studied pedestal effects for spot targets in the isoluminant plane using four-alternative spatial forced-choice. When pedestal and test had the same chromoluminance direction, the threshold rose linearly with pedestal intensity. Thus, the form of their TvC functions is different than those found for Gabor patterns. Facilitation was seen in some cases and in others its absence may be due to there not being any pedestals within the facilitation range. When the pedestal was in one cardinal direction

and the target in the other, they found essentially no effect of the pedestal. They also measured thresholds in eight different chromoluminance directions on pedestals in 16 color directions at one pedestal intensity. Some of the results suggest that more than three mechanisms mediate detection. Although it is possible that there are more chromatic mechanisms for spots than for gratings, it seems premature to conclude this.

What stands out in these results on chromoluminance pedestal effects with spots is that there is a lack of cross masking and that cross facilitation, when it occurs, has different properties from those observed for Gabor patterns.

4.1.3. Noise masks

There is a large body of literature on the masking of luminance patterns with luminance noise and this has recently been extended to the masking of chromoluminance patterns by chromoluminance noise. A variety of different types of noise has been used, including both static and dynamic noises. The comparison of noise masking results to pattern masking results is complicated by the practice of describing noise masking results in terms of the target energy instead of the target contrast, which makes it difficult to compare them with pattern masking results (Legge & Viemeister, 1988). Nevertheless, there are differences between masking by noise and masking by sinewave or Gabor patterns.

When chromoluminance spots, blobs, and Gabor patterns are masked by dynamic chromoluminance noise, little or no facilitation is found and there is essentially no cross masking (Gegenfurtner & Kiper, 1992; Giulianini & Eskew, 1998). Stromeyer et al. (1999, Figs. 7 and 11) got similar results with masks that would not usually be called noise. However, in common with dynamic noise these masks vary randomly during the presentation of the target. On the other hand, using static one-dimensional noise, Sankeralli and Mullen (1997, Fig. 3) found a small amount of facilitation in some conditions (crossed and uncrossed) and a small amount of cross masking in some conditions. Therefore, the type of noise appears to make a difference.

Differences between masking by Gabor patterns and masking by noise are not surprising. The spatial frequency and phase spectra of visual noises are generally much more complex than the usual pattern masks and dynamic noise almost certainly adds variance to neural signals, thereby decreasing discriminability between noise and pattern plus noise. The noise masking model that is commonly used to describe data (Pelli, 1985) is different from current models of pattern masking (Foley, 1994; Watson & Solomon, 1997). The principal difference is that noise masking is explained by the presence of noise energy within the detecting channel, while pattern masking is explained by divisive in-

hibitory inputs to the detecting channel which may come from a wide range of channels and by negative excitation of the detecting channel by the mask.

4.1.4. Other related phenomena

Studies of chromoluminance discrimination after chromoluminance adaptation (Loomis & Berger, 1979; Krauskopf & Gegenfurtner, 1992; Yeh, Pokorny & Smith, 1993) and habituation to chromoluminance temporal modulation (Krauskopf et al., 1992; Krauskopf, Williams, Mandler & Brown, 1986; Webster & Mollon, 1991) very likely involve some of the same mechanisms and processes that mediate pedestal effects. These paradigms differ sufficiently from ours, however, that we do not consider them here.

4.2. Interaction of mechanisms

Earlier studies of masking using chromoluminance patterns focused on the question of whether and how luminance and isoluminant patterns would interact (De Valois & Switkes, 1983; Switkes et al., 1988). One goal of these studies was to test the hypothesis that pathways carrying luminance and chromatic information do not interact. These authors do not define what is meant by 'pathway', but we understand it to be a sequence of neurons along which a visual signal is transmitted. The earlier studies showed that a luminance pattern was masked but not facilitated by a green/red pattern and that a green/red pattern was both facilitated and masked by a luminance pattern, but only at contrasts well above the pedestal threshold (De Valois & Switkes, 1983; Switkes et al., 1988). Our study confirms both of these results.

We can get from these results to conclusions about pathway interactions only in the context of assumptions that link performance to pathway properties. Neither cross-facilitation nor cross-masking by themselves imply anything about interpathway interactions. If we make the common assumption that a pedestal will not influence the detection of a target unless signals produced by the two stimuli affect a common pathway at some stage, it follows that our isoluminant and luminance stimuli affect at least one common pathway. Since both classes of stimuli facilitate the detection of isoluminant stimuli, they affect the pathways that detect our isoluminant stimuli. However, pathway *interaction* does not follow. It may simply be that the pathways that detect isoluminant stimuli are also excited by our luminance stimulus. Several models explain facilitation as due to excitation of the detecting pathway by the pedestal (Legge & Foley, 1980; Wilson et al., 1983; Ross & Speed, 1991; Foley, 1994). Some models explain masking in the same way (Legge & Foley, 1980; Wilson et al., 1983). Recent models, however, do not (Foley, 1994; Watson & Solomon, 1997).

If we assume that our luminance stimuli are detected via a pathway that is not excited by individually isoluminant stimuli and that therefore the isoluminant signals are carried by other pathways, then since masking of a luminance by an isoluminant pattern occurs it does follow that signals in the isoluminant pathways must influence those in the luminance pathway. This assumption seems reasonable because (1) the isoluminant stimuli have been tailored not to excite the luminance pathway, and (2) they do not facilitate detection of our luminance stimulus. The converse statements cannot be made about our luminance pedestal. Thus, a qualitative description of our results together with the above assumptions allow us to conclude only that the pathways carrying signals produced by isoluminant stimuli influence the response of pathways carrying signals produced by luminance stimuli. The model that we will propose in the accompanying paper is consistent with this analysis and asserts further that there are three chromoluminace pathways and that each one interacts with the others by contributing to the divisive inhibitory input to them.

4.3. Implications for models

Our results exclude a broad class of models in which a given target is detected by a single mechanism that consists of a linear receptive field followed by a static non-linearity. Such models allow for only two forms of TvC function depending on whether the pedestal positively or negatively excites the detecting mechanism. Other changes in the pedestal can only shift these functions along the pedestal contrast axis (Foley, 1994). There is no possible contrast metric that will make our results consistent with such models. The broad class of excluded models includes those in which the excitation-response function is linear, concave downward (as in Fechner's Law), or S-shaped (Legge & Foley, 1980; Wilson et al., 1983). The flexibility of these models can be increased by allowing more than one mechanism to contribute to detection (e.g. line-element models, Wyszecki & Stiles, 1982). However, models of this kind cannot account for wide variation in the magnitude of facilitation when different pedestals are paired with the same target (Foley, 1994; Foley & Chen, 1999). In our data, an example of such variation can be seen in the TvC functions for the green/red targeted paired with luminance, green/red, and blue/yellow pedestals (Fig. 3).

On the other hand, the forms of the TvC functions found for chromoluminance patterns in this study and the way in which the functions for a target vary as the pedestal changes are consistent with the model proposed by Foley (1994) for luminance pattern masking. This model postulates both excitatory and divisive inhibitory inputs to pattern vision mechanisms whose response is a nonlinear function of the two inputs. According to this model facilitation is due to the excitation of the detecting

mechanism by the pedestal; masking is due to divisive inhibition produced by the pedestal. Thus, the model interprets the finding that all of our targets were masked by all of our pedestals as indicating that all the pathways that detect these targets are divisively inhibited by the pathways that carry all the pedestal signals. A generalization of this is that all chromoluminance pathways tuned to the same spatial frequency and orientation divisively inhibit all other such pathways. The relatively broad tuning of facilitation indicates that each pathway is excited by a broad range of chromoluminance directions. The high contrast facilitation produced by a luminance pedestal on a isoluminant target indicates that the mechanism which detects the isoluminant target has low excitatory sensitivity to the luminance pedestal. The fact that masking occurs at still higher contrasts indicates that the luminance stimuli also produced a weak divisive inhibition to this mechanism. The similarity of TvC functions for the green/red, blue-green/orange and yellow-green/purple targets suggest that detection of all of them is mediated by the same mechanism.

Thus, the Foley (1994) model is qualitatively consistent with these results and provides an interpretation of the principal effects. However, this model makes an assumption about the independence of the effects of stimulus components, that is almost certainly not satisfied by all the conditions in the present experiment. In the companion paper, we elaborate the Foley (1994) model to overcome this limitation and to provide a quantitative description of our data. Our formulation incorporates the trichromacy of human vision and the known spectral sensitivities of the L, M, and S cones.

Appendix A. Determination of individually isoluminant planes

To determine the individually isoluminant plane for each observer, we used a flicker photometric procedure. Observers viewed two patterns in alternation. One was a luminance Gabor pattern with chromoluminance direction $[0.577, 0.577, 0.577]^T$ in the cone contrast space and a fixed contrast of -30 dB. This is called the reference pattern. The other pattern was also a Gabor, but was modulated along a different line in color space and had an adjustable contrast. This is called the test pattern. Six test patterns were used. The test directions were $[0.408, 0.408, 1.115]^T$, $[0.165, 0.845, 0.908]^T$, $[0.065, 1.026, 0.408]^T$, $[0.165, 0.845, -0.092]^T$, $[0.408, 0.408, -0.299]^T$, and $[0.752, -0.210, 0.408]^T$ in the cone contrast space. All Gabor patterns were horizontal with spatial frequency 1 cpd and scale parameter 1 degree. The temporal frequency of the flicker was 18.75 Hz and each presentation of the flickering stimulus had a duration of 406 ms.

The observer's task was to adjust the contrast of the test pattern to minimize flicker visibility. The flickering stimulus was presented repeatedly until the observer was satisfied with his or her setting. For each test pattern, minimum flicker contrast was taken as the mean of six replications.

Suppose the cone contrast sensitivities of the luminance mechanism are S_L, S_M, and S_S where the subscripts L, M, and S denote the three cone types. In vector form, the sensitivity vector of the luminance mechanism is $SEN = [S_L, S_M, S_S]$. The reference grating has a direction $CD_r = [0.577, 0.577, 0.577]^T$ in the cone contrast space and -30 dB contrast. Denote the chromoluminance direction of a test grating $CD_t = [CD_L, CD_M, CD_S]^T$ and suppose that the corresponding minimum flicker contrast is C_t. If the luminance mechanism is linear (as is commonly assumed) and if minimum flicker occurs when the reference and test patterns produce the same response in the luminance mechanisms, then for each test pattern

$$C_r \cdot SEN \cdot CD_r = C_t \cdot SEN \cdot CD_t. \tag{A1}$$

With data obtained for $N \geq 2$ test patterns, the N equations of the form of ($A1$) may be solved to determine the chromoluminance direction of SEN. Table 3 provides the values of SEN we determined for each of our three observers.

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