Pergamon

0042-6989(94)00098-0

Vision Res. Vol. 34, No. 23, pp. 3139–3144, 1994

0042-6989/94 $7.00 + 0.00

The Time–Course of Chromatic Facilitation by Luminance Contours

RHEA T. ESKEW JR,*† CHARLES F. STROMEYER III,*‡ RICHARD E. KRONAUER*

Received 16 August 1993; in revised form 11 March 1994

The threshold for detecting an equiluminant chromatic spot is approximately halved by the presentation of a coincident, suprathreshold luminance pedestal flash. The dynamics of this facilitation were studied by varying the duration and temporal asynchrony of the chromatic test flash and luminance pedestal. Facilitation occurs in a narrow temporal window near the chromatic test presentation; masking may occur when the pedestal is temporally displaced from the test by longer times. The mechanism producing facilitation lags behind the chromatic signal by at least 20 msec.

Contour–color interactions Chromatic facilitation Luminance contour Temporal properties Color vision

INTRODUCTION

At threshold, there are independent luminance and chromatic detection mechanisms (Cole, Stromeyer & Kronauer, 1990; Krauskopf, Williams & Heeley, 1982; Stromeyer, Cole & Kronauer, 1985, 1987). The mechanisms may interact in important ways when one signal is suprathreshold. For example, in the gap effect, the color difference between equiluminant regions may be more detectable when a visible contour divides the regions (Boynton, Hayhoe & MacLeod, 1977; Eskew, 1989). Similar chromatic facilitation by luminance patterns has been observed with square-wave (Hilz & Cavonius, 1970; Hilz, Huppmann & Cavonius, 1974) and sine-wave gratings (Switkes, Bradley & De Valois, 1988) and with circular flashes on a large field (Cole *et al.*, 1990; Eskew, Stromeyer, Picotte & Kronauer, 1991; Hilz *et al.*, 1974; Nick & Larimer, 1983).

Cole *et al.* (1990) measured how a suprathreshold luminance flash, or pedestal, affected the visibility of a weak simultaneous, coincident red or green chromatic flash. A 1 deg suprathreshold luminance disk pedestal was flashed for 200 msec in both temporal intervals of a two-alternative forced-choice (2AFC) trial; the chromatic test was added to the pedestal in one interval. The chromatic threshold was reduced about two-fold and the slope of the psychometric function was reduced from about 2.0 to about 1.2. The facilitative effect of the luminance pedestal was independent of its intensity, once the pedestal was clearly visible, and there was little or no masking of chromatic detection even at very high pedestal intensities.

Several mechanisms have been proposed to account for the chromatic facilitation. Without the pedestal, the liminal chromatic flash appears diffuse and poorly localized in time and space. The luminance pedestal might decrease this uncertainty, and thereby reduce threshold (Pelli, 1985); the flatter psychometric function is consistent with this view. However, Eskew *et al.* (1991) showed that the facilitation is not solely caused by uncertainty reduction; facilitation occurred even in a yes–no procedure after data were corrected for guessing, which should eliminate uncertainty effects (Pelli, 1985), and the slopes of chromatic ROC functions were the same whether or not a pedestal was used. A second possibility is that the edges provided by the luminance pedestal may better demarcate the test region, promoting appropriate chromatic integration or filling-in. When the pedestal is not present, the chromatic mechanism may integrate over too large an area, diluting its signal (Boynton *et al.*, 1977; Eskew, Stromeyer & Kronauer, 1995; Nick & Larimer, 1983). Cole *et al.* (1990) demonstrated that the chromatic facilitation was identical when measured with a uniform luminance disk or a thin ring that surrounded the test, showing that it is the edge of the pedestal that produces the facilitation. The observer presumably compares the color of the demarcated test region with the surround, for the facilitation disappears when the surrounding comparison field is made dark (Cole *et al.*, 1990; Nick & Larimer, 1983; Wandell, 1985).

Any of these mechanisms for facilitation would take a finite time to occur. For the pedestal to promote accurate chromatic integration, the luminance edges would have to be extracted, and then this information

*Division of Applied Sciences, Harvard University, Cambridge, MA 02138, U.S.A.
†Department of Psychology, 125-NI, Northeastern University, Boston, MA 02115, U.S.A. [*Email* eskew@neu.edu].
‡Department of Psychology, Harvard University, Cambridge, MA 02138, U.S.A.

would have to be combined with the chromatic signal. We attempt here to find the minimum time taken by the facilitation mechanism. Our experiments explored the time–course of chromatic facilitation by varying the temporal offset of the chromatic test flash and luminance pedestal.

METHODS

Apparatus

Stimuli were produced with an eight-channel Maxwellian view (Cole *et al.*, 1990). The stimulus consisted of coincident, 1 deg central test disks of red, green and yellow, and matched contiguous annuli (6.2 deg outer diameter), each composed of light from light-emitting diodes (LEDs) passed through interference filters. These components were superposed on an intense yellow (579 nm) adapting field of 6.2 deg diameter. The entire stimulus appeared as a uniform yellow disk between trials. The test area was fixated with the aid of two dark dots separated by 3 deg, placed above and below the test. The total illuminance was typically ~3000 td, with the LEDs contributing less than 400 td. All light components were narrow-band (8–10 nm half-band-width). The spectral centroids of the filtered red, green, and yellow LEDs were 671, 551 and 579 nm. The yellow main field matched the yellow LED and the sum of red and green LEDs. Absolute radiance was calibrated each session.

Procedure

The observer adapted for several minutes to the field, and then the chromatic test threshold was measured with the two-alternative forced-choice QUEST procedure (Watson & Pelli, 1983). The two temporal intervals of each trial were marked by tones, typically separated by 400 msec. The test was presented in one interval chosen randomly, and the observer received response feedback. The chromatic sign of the test, red or green, was constant for a run. When the luminance pedestal was used, it was identically presented in both intervals of each trial and was constant in contrast for the run. To obtain each threshold estimate, the pooled data from several runs were fit by the Weibull psychometric function,

$$P(a) = 1 - \tfrac{1}{2} \cdot \exp[-(a/\alpha)^{\beta}]$$

where $P(a)$ is the probability of a correct response for a stimulus of contrast a, $\frac{1}{2}$ is the probability of a correct response by chance, α is the threshold (the 82% correct point) and β is the slope. Error bars in the figures represent 90% χ^2 confidence intervals around the threshold estimates.

For some conditions, we demonstrated that the chromatic test was explicitly detected with a chromatic mechanism by showing that the threshold for detection of the flash was equivalent to the threshold for identifying the chromatic sign of the test. For the identification task, the flash was randomly either green or red on each trial (Cole *et al.*, 1990). Identification thresholds are plotted as solid diamonds in Figs 2 and 3.

Stimulus representation

Stimuli are specified in long-wave and middle-wave cone contrast coordinates, $\Delta L/L, \Delta M/M$ (Stromeyer *et al.*, 1985; Cole *et al.*, 1990), based on the cone fundamentals of Smith and Pokorny (1975). In these coordinates, incremental and decremental luminance flashes are defined as polar vector angles 45 and 225 deg, and green and red chromatic flashes as 135 and 315 deg. Stimulus contrast for the test and pedestal is specified by vector length in cone contrast space, $[(\Delta L/L)^2 + (\Delta M/M)^2]^{1/2}$.

RESULTS

We first examine whether the chromatic facilitation varies with flash duration when the luminance pedestal and chromatic test are simultaneous. We then displace the luminance pedestal in time relative to the chromatic test, to trace the time–course of the facilitation.

Effect of flash duration on facilitation: simultaneous pedestal and test

Figure 1 shows facilitation of chromatic detection by an incremental, *simultaneous* luminance pedestal of

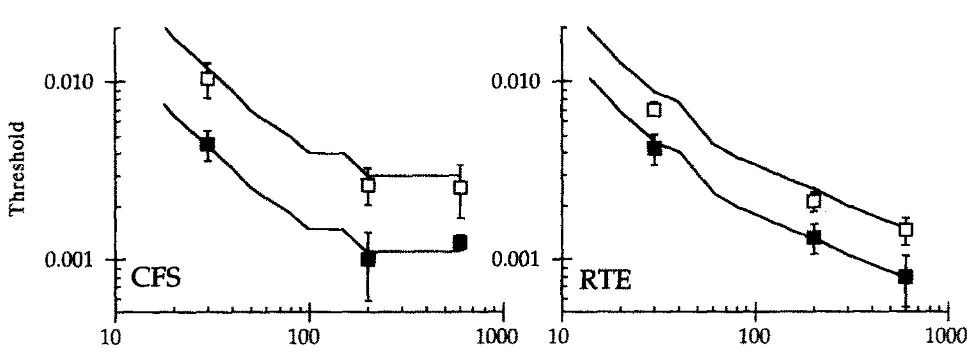

FIGURE 1. Chromatic detection thresholds as a function of duration: measured with no luminance pedestal (open squares) and measured with a simultaneous, coincident luminance pedestal of ~2× threshold (solid squares). The facilitation is similar in magnitude at all durations. The upper solid line connects similar data points for the same observers from Eskew *et al.* (1994, Fig. 5) positioned absolutely; it was slid down to fit the facilitated data.

30, 200 and 600 msec. The pedestal, set to 2.3 times threshold, appeared as a temporally-crisp disk with clear edges. Each point is based on about 30 runs over a 1 yr period. Open squares show the unfacilitated thresholds and solid squares show the facilitated thresholds. The pedestal facilitates chromatic detection approximately equally at all durations, and is appreciably higher for CFS (2.3 ×) than for RTE (1.7 ×)—consistent with previous results (Eskew *et al.*, 1991). RTE is generally more sensitive to chromatic flashes on a uniform field than is CFS; however, the facilitated thresholds are similar for the two observers.

In the remaining experiments, the luminance pedestal was temporally displaced relative to the chromatic test. The pedestal was brief, in order to measure the time–course of the chromatic facilitation. The pedestal was set at 2–3 × threshold.

Brief tests

The open squares in Fig. 2 show how the detection threshold of a 30 msec chromatic test varies as a function of the stimulus onset asynchrony (SOA) of a 30 msec luminance pedestal. Here and throughout, negative SOAs indicate that the pedestal onset preceded test onset. The rectangles on the abscissae mark the occurrence of the test, and the right-most data point in each panel indicates the unfacilitated threshold measured on the uniform field. The top and middle panels show results for CFS, obtained with red (top) and green (middle) chromatic flashes, presented with either decremental luminance pedestals (left, −) or incremental pedestals (right, +). The solid diamonds show chromatic identification thresholds for red and green tests. There is close agreement between detection and identification thresholds, indicating that the tests are detected by

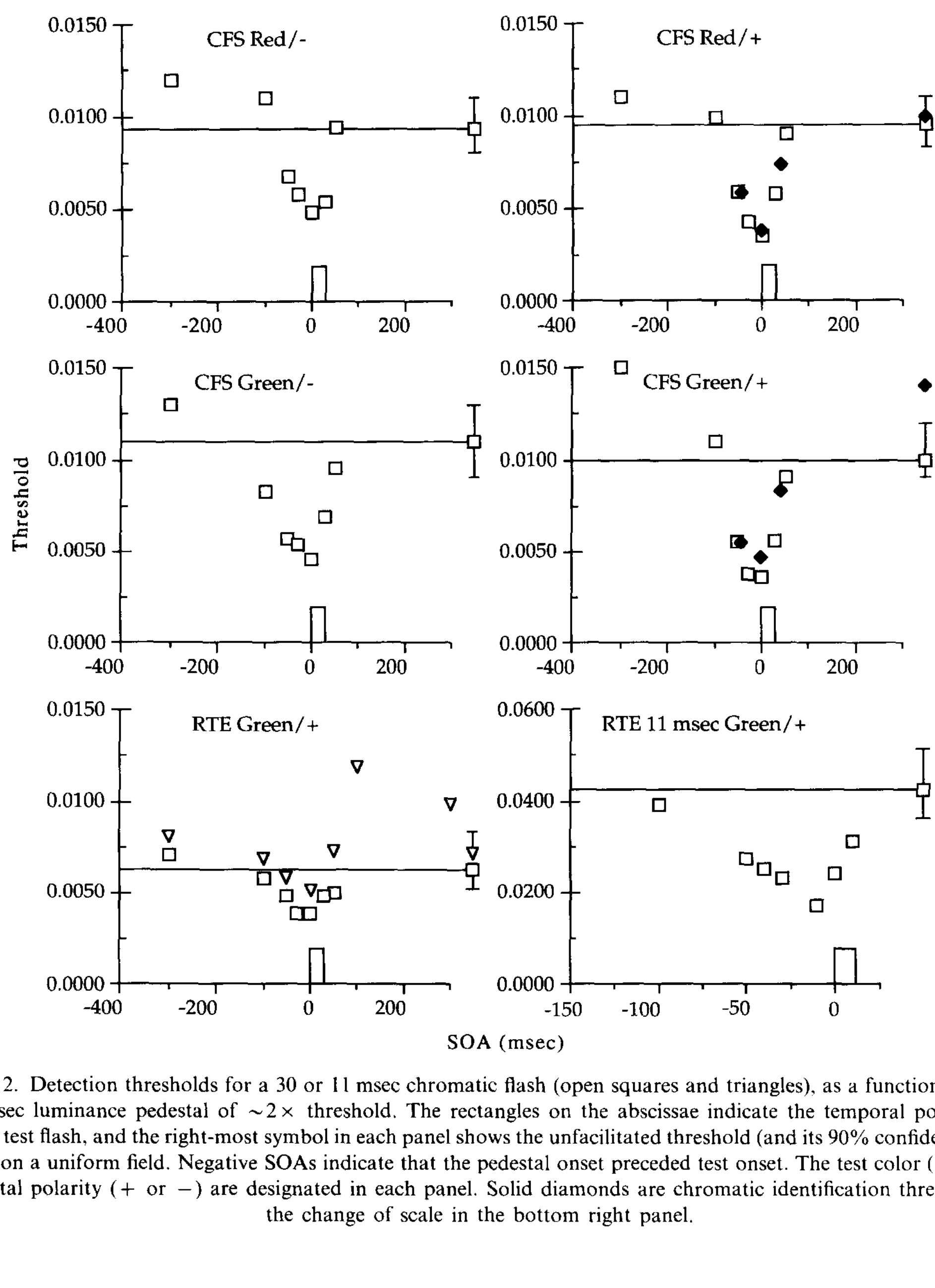

FIGURE 2. Detection thresholds for a 30 or 11 msec chromatic flash (open squares and triangles), as a function of the SOA of a 30 msec luminance pedestal of ∼2 × threshold. The rectangles on the abscissae indicate the temporal position of the chromatic test flash, and the right-most symbol in each panel shows the unfacilitated threshold (and its 90% confidence interval) measured on a uniform field. Negative SOAs indicate that the pedestal onset preceded test onset. The test color (red or green) and pedestal polarity (+ or −) are designated in each panel. Solid diamonds are chromatic identification thresholds. Note the change of scale in the bottom right panel.

chromatic mechanisms. The results in all four panels are nearly identical, extending the finding of Cole *et al.* (1990) that the polarities of a simultaneous test and pedestal are irrelevant to the facilitation. For RTE (bottom left), the test was green; the triangles represent data collected with a procedure in which the 2AFC interval duration was constant throughout (whereas in all other panels the interval varied with SOA length). The two sets of results for RTE are similar, indicating the procedural difference has little effect.

The value of the maximally facilitated threshold is again virtually identical for the two observers. As before, RTE is more sensitive to the chromatic test on the uniform field, and there is less facilitation for RTE than for CFS. The time–course of facilitation is also similar for the two observers. Slight masking occurs when the pedestal precedes the test by 300 msec, and facilitation does not begin until the pedestal precedes the test by < 100 msec. There is also masking near the test offset (lower left panel); this masking is larger than the early masking and lasts at least 300 msec. The facilitation thus occurs in a fairly narrow temporal window, outside of which there is masking. Maximum facilitation occurs when the luminance pedestal is presented between 0 and 30 msec prior to the test, which is surprising since the luminance system has a shorter latency than the chromatic system (Bowen, 1981; Schwartz & Loop, 1983).

To better determine the SOA yielding maximum facilitation, an 11 msec chromatic test was used in the bottom right panel of Fig. 2, with a set of closely spaced SOAs. As before, the luminance pedestal was 30 msec; the field was reduced to 750 td, so that we would have sufficient test light. An SOA of − 10 msec produced the greatest facilitation.

For the results in Fig. 2, the Weibull slope parameter β (not plotted) was correlated 0.60–0.85 with the threshold parameter α, confirming the finding that the pedestal reduces both the threshold and the slope of the psychometric function (Cole *et al.*, 1990; Eskew *et al.*, 1991). Pedestals which produced masking tended to raise the slope of the psychometric function.

Long tests

The preceding results were obtained with a brief chromatic test and a 30 msec pedestal. We now probe chromatic sensitivity for a sustained chromatic test of 200 or 600 msec, using the same brief pedestal.

Figure 3 shows detection thresholds (open squares) and chromatic identification thresholds (solid diamonds) for the 200 msec chromatic flash, and Fig. 4 shows detection thresholds for the 600 msec chromatic flash. Certain features of the results are similar to Fig. 2; there is weak masking when the pedestal precedes the test by 300 msec, facilitation begins prior to the test, and masking occurs after test offset. With the long chromatic tests, the maximal facilitation occurs 50–100 msec *after* test onset, rather than 10–30 msec prior to it, as was observed with the brief chromatic flash. This difference can be explained by the expected response of the chromatic system for the two stimuli, based upon the chromatic impulse response functions (IRFs) measured by Eskew, Stromeyer and Kronauer (1994). The peak response to the 200 and 600 msec chromatic flashes occurs later than the peak response to the 11 or 30 msec flashes. The later time of maximal facilitation for the long chromatic flashes is likely caused by this longer chromatic rise time.

With the 200 and 600 msec chromatic flashes, there is a tendency for the facilitated thresholds to rise slightly over the course of the flash. This might be explained by a chromatic IRF with a negative lobe (Eskew *et al.*, 1994a): the step response of a filter with a biphasic impulse response rises toward a peak until the time of the filter's zero-crossing, and thereafter declines. Thus, the negative portion of the chromatic IRF could account for the threshold rise during the chromatic flash.

The observed rise is small. To measure it more carefully, we presented the 30 msec pedestal at SOAs of

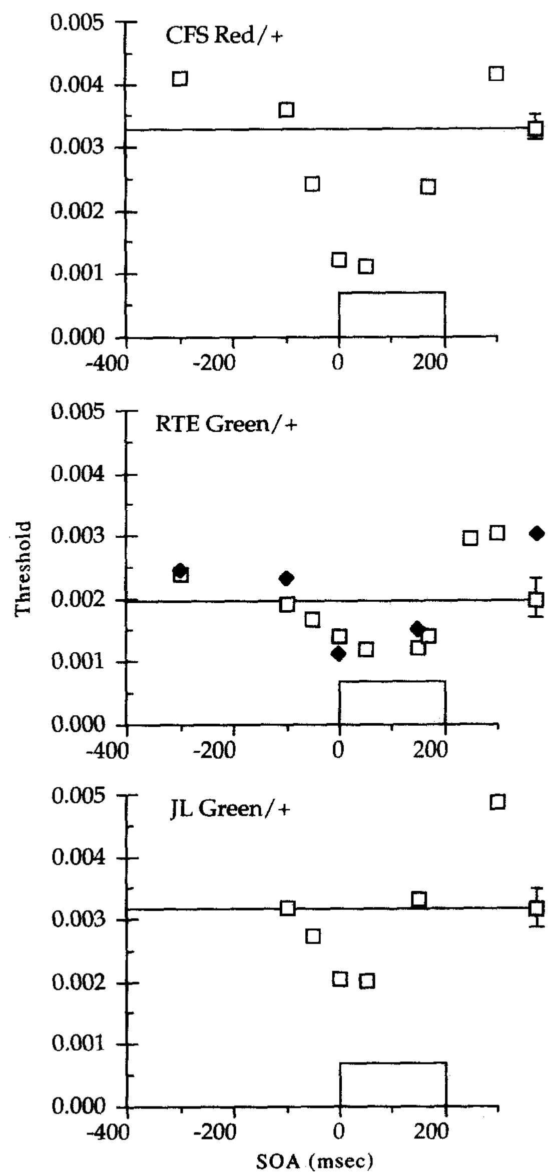

FIGURE 3. Detection thresholds (open squares) for a 200 msec chromatic flash, as a function of the SOA of a 30 msec luminance pedestal at ~2× threshold. The rectangles on the abscissae indicate the temporal position of the test flash. Solid diamonds are chromatic identification thresholds.

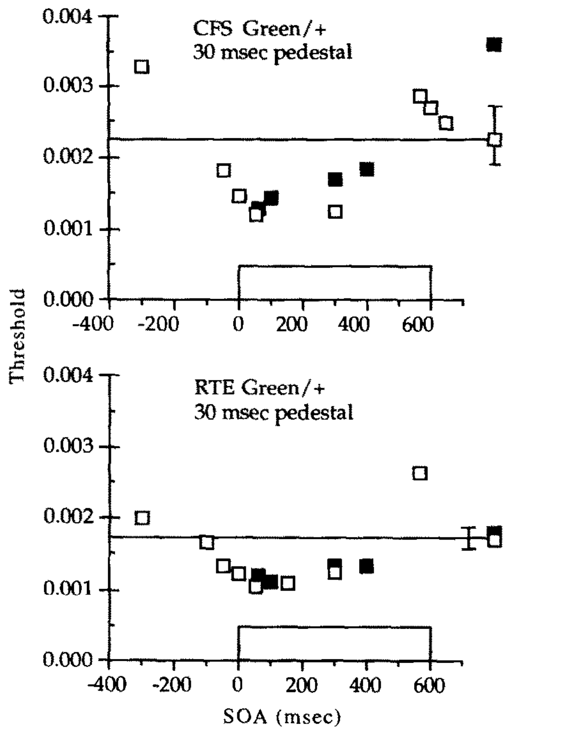

FIGURE 4. Detection thresholds for a 600 msec chromatic flash, as a function of the SOA of a 30 msec luminance pedestal of ~2× threshold. For the solid symbols, the four SOAs were randomly intermixed within each run.

60, 100, 200 and 400 msec, relative to the onset of the 600 msec green chromatic test, with the SOAs randomly intermixed in each run. The delay between the warning tone and the test was varied so that the pedestal always occurred 400 msec after the tone. Retinal illuminance was 1500 td for CFS, and 2000 td for RTE. These chromatic thresholds are shown in Fig. 4 as solid squares. Facilitation is greatest 60–100 msec after test onset and thresholds then rise slightly.

Two features of the data in Figs 3 and 4 confirm that the chromatic impulse response has a negative lobe. First, the facilitated thresholds generally rise over the duration of the 600 msec test flash, as expected from a biphasic impulse filter as noted previously. Second, there was masking when the pedestal occurred just after the test, and the pedestal often appeared of a hue complimentary to the test.

Appearance of the brief pedestal with various tests

The chromatic test by itself appeared extended in time, even when presented for only 30 msec (Schwartz & Loop, 1982, 1983). When the brief pedestal was presented 100–300 msec before the chromatic test, observers reported two events: a brief, crisp, luminance flash, followed by an extended chromatic blob. At other SOAs the test and pedestal were usually perceived as a single event—a brief luminance pedestal weakly tinged with color. This percept occurred even when the 30 msec pedestal was presented mid-way through the long 600 msec chromatic test—there was little hint that the chromatic stimulus preceded and followed the pedestal.

DISCUSSION

When the chromatic test and luminance pedestal were presented simultaneously, chromatic facilitation was approximately constant for different flash durations over the range 30–600 msec. The size of facilitation differed between observers, but the absolute level of the facilitated thresholds was similar for the two observers. The approximately constant facilitation across durations has an important implication. A chromatic temporal filter with reasonable parameters will have a larger peak and a larger integral for a 200 msec flash than a 30 msec one. If facilitation represents an increased gain, then the constant facilitation indicates that the amplified chromatic signal must saturate. Because both the peak and the integral increase with duration, saturation of the facilitation is required whether we assume either peak detection or temporal probability summation. The saturation could explain why facilitation never exceeds about two-fold, and why CFS and RTE have very similar facilitated thresholds even though their unfacilitated thresholds differ.

Perhaps the most surprising of our results is the masking at many SOAs. A simultaneous luminance pedestal produces little or no chromatic masking, even at high pedestal intensities (Cole *et al.*, 1990). When the pedestal preceded the test by a relatively large interval, the luminance disk made it harder to detect the chromatic test. When the pedestal was presented just before the test (SOA −100 msec or closer), the pedestal facilitated the chromatic test, making it easier to detect. With brief stimuli (30 msec), maximal facilitation occurred when the pedestal onset occurred 10–30 msec prior to the test onset. As the pedestal was presented later in time, extending after the chromatic test, the luminance pedestal again produced masking. Eskew *et al.* (1994) showed that the opposite-colored rebound seen at the offset of the chromatic flash could be facilitated by a luminance pedestal presented immediately following the test (the pedestal and test did not temporally overlap). In that experiment, the observer concentrated only on the appearance of the pedestal to make a judgment. The task in the present experiment was to detect the test flash, and there may have been confusion when the test appeared of one color and the pedestal of a different color, thus resulting in some masking.

For SOAs producing facilitation, the test and pedestal generally appeared as *one* event: the observer saw a sharp-edged luminance pedestal weakly tinged with color that was confined to the pedestal duration. This was generally true even when the test and pedestal were of greatly different durations, e.g. when the 30 msec pedestal occurred mid-way through the 600 msec chromatic test flash. Luminance contours are thought to confine the spatial spreading or filling-in of chromatic signals (Boynton *et al.*, 1977; Eskew, 1989; Gregory, 1977; Nick & Larimer, 1983). The current results suggest that luminance contours may also *temporally* confine the appearance of the chromatic signals.

Figure 2 shows that maximal facilitation occurs when the pedestal *precedes* the test, by 10–30 msec. This ~20 msec period is a *lower bound* on the actual time required for facilitation, since the luminance mechanism probably has a shorter latency than the red–green chromatic mechanism (Schwartz & Loop, 1982, 1983). The time required for facilitation is the sum of this latency difference and ~20 msec.

REFERENCES

Bowen, R. W. (1981). Latencies for chromatic and achromatic visual mechanisms. *Vision Research, 21*, 1457–1466.

Boynton, R. M., Hayhoe, M. M. & MacLeod, D. I. A. (1977). The gap effect: Chromatic and achromatic visual discrimination as affected by field separation. *Optica Acta, 24*, 159–177.

Cole, G. R., Stromeyer, C. F. III & Kronauer, R. E. (1990). Visual interactions with luminance and chromatic stimuli. *Journal of the Optical Society of America A, 7*, 128–140.

Krauskopf, J., Williams, D. R. & Heeley, D. W. (1982). Cardinal directions of color space. *Vision Research, 22*, 1123–1131.

Eskew, R. T. Jr (1989). The gap effect revisited: Slow changes in chromatic sensitivity as affected by luminance and chromatic borders. *Vision Research, 29*, 717–719.

Eskew, R. T. Jr, Stromeyer, C. F. III & Kronauer, R. E. (1994). Temporal properties of the red–green chromatic mechanism. *Vision Research*, **34**, 3127–3137.

Eskew, R. T. Jr, Stromeyer, C. F. III & Kronauer, R. E. (1995). Enhancement of colour visibility by partial luminance boundaries. In preparation.

Eskew, R. T. Jr, Stromeyer, C. F. III, Picotte, C. J. & Kronauer, R. E. (1991). Detection uncertainty and the facilitation of chromatic detection by luminance contours. *Journal of the Optical Society of America A, 8*, 394–403.

Gregory, R. L. (1977). Vision with isoluminant colour contrast: 1. A projection technique and observations. *Perception, 6*, 13–19.

Hilz, R. & Cavonius, C. R. (1970). Wavelength discrimination measured with square-wave gratings. *Journal of the Optical Society of America, 60*, 273–277.

Hilz, R. L., Huppmann, G. & Cavonius, C. R. (1974). Influence of luminance contrast on hue discrimination. *Journal of the Optical Society of America, 64*, 763–766.

Nick, J. & Larimer, J. (1983). Yellow/blue cancellation on yellow fields: Its relevance to the two process theory. In Mollon, J. D. & Sharpe, L. T. (Eds), *Colour vision: Physiology and psychophysics* (pp. 375–383). London: Academic Press.

Pelli, D. G. (1985). Uncertainty explains many aspects of visual contrast detection and discrimination. *Journal of the Optical Society of America A, 2*, 1508–1532.

Schwartz, S. H. & Loop, M. S. (1982). Evidence for transient luminance and quasi-sustained color mechanisms. *Vision Research, 22*, 445–447.

Schwartz, S. H. & Loop, M. S. (1983). Differences in temporal appearance associated with the activity in the chromatic and achromatic systems. *Perception & Psychophysics, 33*, 388–390.

Smith, V. C. & Pokorny, J. (1975). Spectral sensitivity of the foveal cone photopigments between 400 and 500 nm. *Vision Research, 15*, 161–171.

Stromeyer, C. F. III, Cole, G. R. & Kronauer, R. E. (1985). Second-site adaptation in the red–green chromatic pathways. *Vision Research, 25*, 219–237.

Stromeyer, C. F. III, Cole, G. R. & Kronauer, R. E. (1987). Chromatic suppression of cone inputs to the luminance flicker mechanism. *Vision Research, 27*, 1113–1137.

Switkes, E., Bradley, A. & De Valois, K. K. (1988). Contrast dependence and mechanisms of masking interactions among chromatic and luminance gratings. *Journal of the Optical Society of America A, 5*, 1149–1162.

Wandell, B. A. (1985). Color measurement and discrimination. *Journal of the Optical Society of America A, 2*, 62–71.

Watson, A. B. & Pelli, D. G. (1983). QUEST: A Bayesian adaptive psychometric method. *Perception & Psychophysics, 33*, 113–120.

Acknowledgements—Research supported by NIH EY-01808, NIH EY-09712, AFOSR 86-0338 and AFOSR 89-0304.